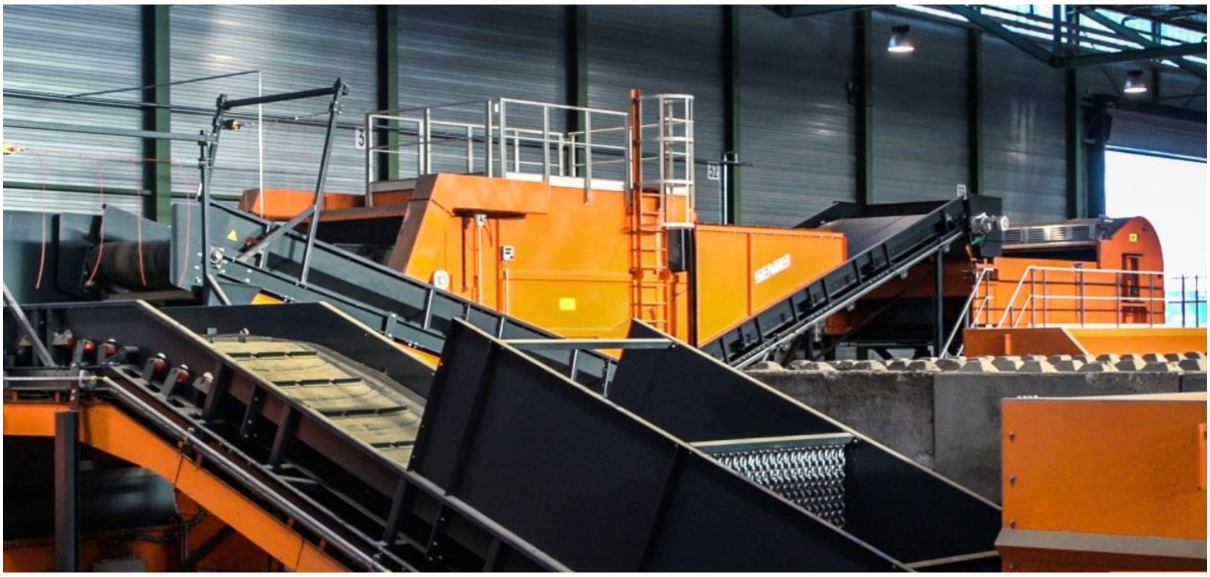
Reducing waiting times in an engineer-to-order production environment



Bachelor Thesis Industrial Engineering & Management

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SENRO

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Bachelor thesis information

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Management summary

This research has been conducted at Senro in Hengelo. Senro produces sorting lines and -machineries according to customer specifications. At the start of the research, interviews were done with stakeholders. Based on these interviews, we constructed a problem cluster, in which the action problem is that the on-time delivery performance is lower than desired. Several problems are identified as potential causes of low on-time delivery performance. The core problem of the research is that there is no insights on the waiting time of modules between production phases. Stakeholders also mentioned that modules were sometimes waiting quite long before moving on to the next production phase. That is why the focus of this research is on identifying the waiting times and come up with ways to reduce them. This resulted in the following main research question:

What are the causes of modules waiting between production phases at Senro and how can they be reduced?

With the current situation analysis, which was mostly done with data analysis and interviews, we identified the flow of modules in terms of time and routing as well as some causes of waiting times by analyzing seven large projects. The total production lead time is 29.36 working days on average. Furthermore, we determined on *module level* how long a module was at certain production as well as when it entered and exited that phase on average. With this information a timeline is constructed, in which the average waiting times between production phases can be seen.

Then the welding and assembly department are chosen as bottlenecks. The main reason for this is that the waiting times are the highest before these departments. Another reason for not including the laser cutting and bending phase is that the data available on these phases is not good or cannot be used to provide valuable insights.

In the literature review, we look at the Quick-Response manufacturing (QRM) theory and causes of waiting time and, from this factors that contribute to waiting times were identified and how to reduce them. Utilization level has the most impact on waiting times, followed by the average variability and processing time for a module. Reducing these factors, leads to a reduction in waiting times as well.

In order to test possible solutions, a Monte Carlo simulation model is build. With this model we can simulate the performance of the welding and assembly department in the current situation in terms of expected waiting times, but also expected amount of overtime days and overtime hours needed. With the model, a custom scenario can be simulated to experiment with different scenario's. Based on the experiments, we know what has an impact on the performance of the welding and assembly departments. Therefore, by first doing the experiments and taking the literature review into account we can come up with relevant solutions. The following five solutions, of which the first two focus on reducing variability and last three on reducing utilization levels, are tested in the Monte Carlo simulation model:

- Reducing variability in workload on a day
- Reducing variability in employees present
- Increasing effective capacity
- Adding capacity (employee)
- Outsourcing work

The first two solutions based on reducing the variability give mixed results. Reducing the variability in workload on a day only affects the expected waiting time. Halving variance of workload on a day results in a reduction of 1.27 working days of waiting time, which is a 4.33% reduction of the total

production lead time. Other variables like expected overtime days and overtime hours are not affected by this solution. Reducing the variability in employees present gives completely different results. When variance in employees on a day is reduced the expected waiting time barely changes, however there is an improvement in amount of expected overtime days and overtime hours needed.

The last three solutions based on reducing utilization levels give similar results, but differ in effectiveness. Increasing the effective capacity means improving the efficiency of work to get more done in less time. An increase of 5% in effective capacity is assumed to be possible. This leads to a reduction of 2.90 working days expected waited, a 9.90% reduction of the total production lead time. Adding capacity in the form of an extra employee has a massive impact on the production process. Doing this ensures a utilization below 85% that QRM advises. We find that adding one flexible employee that can work for 70% of the time in welding and 30% in assembly gives the lowest combined expected waiting time. Waiting time decreases by 4.43 working days, which is a reduction of 15.1% of the total production lead time and expected overtime days and overtime hours improve drastically. The final solution that we test is the effect of outsourcing work. Outsourcing 10% of welding work and 5% of assembly work is advised when choosing this solution. This leads to a reduction of 4.23 days in waiting time, a 14.4% decrease of the total production lead time. Expected overtime days and overtime hours decrease significantly as well. The last two solutions should not be combined. Both of these last two solutions are ranked as number one for being the best solutions based on feasibility, impact and cost.

Solutions on reducing the utilization levels have a bigger impact on waiting time than the solutions on reducing variability. The biggest challenge of implementing the last two solutions is to get management on board. This solution is based on QRM theory where utilization is advised to not be higher than 85 percent. This is much different to traditional ways of working. QRM says it is worth it, since waiting times become less, the production environment becomes less uncontrolled and there is more time to work on improving.

Based on the research, some recommendations could be made to Senro of which the following are the most important:

- If Senro wishes to reduce waiting time and is convinced that lower utilization helps their production process, we recommend either to add flexible capacity where the extra person works for 70% of the time in the welding department and 30% in the assembly department or we recommend to outsource 10% more work of welding and 5% of the assembly department.
- It is recommended to divide the workload on a day more evenly across the years. Currently the workload on a day is fluctuating quite a bit. This means some periods have extreme peaks in workload, which asks a lot of the employees. Reducing the variance in workload on a day reduces the expected waiting time.
- The Monte Carlo simulation can be used to evaluate the performance of the welding and assembly department.
- In order to get a more accurate insight into the performance of the production process, it is recommended to track data on part-level rather than on module-level. Currently possibilities of ERP-systems are looked at, meaning that Senro is already working on this recommendation. The result is that future research is more effective and efficient.
- Increasing effective capacity is a good way to reduce waiting time due to the reduction of utilization levels. In this research, it is not explained how this can be achieved specifically at Senro. Future research on how to increase the effective capacity in the different production phases will be useful in decreasing the expected waiting time.

Preface

Dear reader,

In front of you lies the thesis that concludes my Bachelor Industrial Engineering and Management at the University of Twente. From April 2021 until July 2021 I performed this research at Senro BV in Hengelo. The goal of the assignment is to provide some insights into the waiting times that occur in the production process at Senro and come up with ways to reduce them. I learned a lot about the organization and the topic and how do a research by myself. For this I would like to thank some people.

First I would like to thank my supervisor Mark Mensen for bringing me into Senro and especially for the guidance during the start of the research. Without his help this thesis would not be possible. Furthermore, I would like to thank the other employees that were willing to help me with interviews and answering the questions I had. Being able to work at the company even during Corona helped with the motivation and the working atmosphere was very pleasant.

I would like to thank Engin Topan for being my lead supervisor. In our meetings we had some good discussions about the thesis and how to proceed. These meeting always seemed to come at the right moment and were always useful to me. Thanks to Ipek Seyran Topan as well for being my second supervisor.

Last but not least, I want to thank family and friends for the support and interest in my thesis.

Niels van Boxel

Hengelo, July 2021

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1. Introduction

This bachelor thesis is conducted at Senro BV. Focus points of the research is a better insight in the flow in the production area and reducing the times that module are waiting between production phases. Modules are parts of a project, consisting out of multiple parts. This chapter introduces the thesis to the reader. In Section 1.1, the company Senro is introduced, to give the reader a good insight into what kind of company Senro is. Section 1.2 identifies the action problem and core problem. Finally, in Section 1.3 the research design is presented.

1.1 Company introduction

Senro is a fast growing company designing and producing installations and partial machines for the recycling industry and related sectors. Their products get used for sorting, filtering, separating and transporting of the most diverse materials. Senro delivers products that are tailored to fit the customers unique environment, meaning that they have an Engineer-to-order production approach. (Amrani et al., 2010). Senro was founded in 2012, making them a relatively new company.

The sorting plants, separation machines and sorting techniques of Senro are used in diverse industries worldwide, with most of them in The Netherlands, Germany and Belgium. All the production of their sorting lines and separation machineries is done in Hengelo. Senro takes care of the entire design- and production process. This means that they have their own engineering department, where the products get designed to fit the customer needs. For manufacturing their products, they use advanced machineries and modern welding equipment. Senro also installs the products at the desired location and offers services, such as logistics services or periodic maintenance of equipment. Senro has also proven to be a reliable partner for outsourcing of several activities like laser cutting, bending, turning, welding and assembly. An example of a sorting line, which is one of the type of projects they work on, can be seen in Figure 1.1.

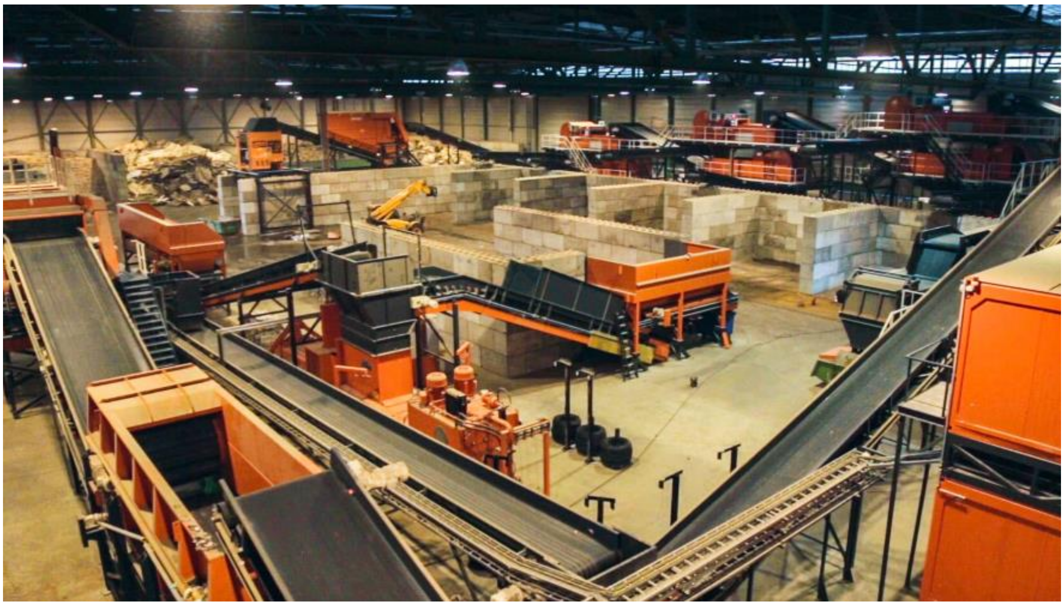

Figure 1.1: Example of sorting line

Senro has grown massively in the amount of employees, warehouse size, numbers of projects they do at a time and many more things. Although growth is great for a company, it also comes with new problems. When there are little projects to be done, planning can be done based on gut feeling and that can be accurate. In the last few years they have improved massively on various departments by making processes more efficient and by keeping track of production processes better. However, they feel like more improvements can be made to reduce the lead time.

1.2 The problem

In this section, the problem that is addressed in this research is presented and motivated. First the action problem is identified, followed by the identification of the core problem with the use of a problem cluster. The core problem is then motivated and made measurable with a norm and reality.

1.2.1 Identification action problem

Senro has problems with delivering projects on time. This is a result of the fact that the company has grown massively, especially in the last 6 years. Planning is, despite the massive growth, still done mostly based on gut feeling. It has become harder to keep control over the years. Currently the company does not really have a good overview of how orders are flowing between different phases in the production. They have a limited availability of usable data, which makes it hard for them to make predictions on how long certain tasks will be taking and how much needs to be outsourced. All of this causes the production to be quite uncontrolled and decisions are made spontaneously.

Not having a structured planning makes the working environment uncontrolled, which leads to longer lead times for the projects. In the current planning they plan based on 'gut feeling' and emergency cases take priority in the production process, causing other projects to be delayed. The delays are causing the lead times to be longer, which in turn results in a lower on-time delivery performance. Having an on-time delivery performance that is lower than desired results in customer dissatisfaction and a more uncontrolled working environment, but on top of that is also an indicator that the efficiency of production may not be at the level it should be. In cooperation with Senro the action problem was formulated as follows:

"The on-time delivery performance is currently lower than the 90% they want it to be."

The on-time delivery performance is the percentage of orders that is finished within the agreed to delivery date. A reduced customer satisfaction can lead to a lower amount of orders placed. The norm for the on-time delivery performance is 90%, however currently they are not tracking their delivery performance exactly, but is certain that the reality is lower than 90%.

1.2.2 Identification core problem

In order to come to the root of the problem Senro faces, it is time to find out which problems contribute to the action problem. A problem cluster will be presented in which all problems and their connections are mapped (Heerkens and van Winden, 2017). With the use of the problem cluster a clear overview can be made of the problem context and the core problem can be identified in a straightforward way. First off the problems that were found related to the action problem are described and then their relations are mapped in the problem cluster. These problems were found by doing interviews with various stakeholders within different departments within the company.

A problem that returned in all of the interviews is that the stakeholders think the working environment is uncontrolled and sometimes even chaotic. This has many underlying problems. First of all, emergency cases cause a lot of disruption as they get priority over the current production planning. Another cause for the uncontrolled working environment is that it is hard to make structured planning currently.

The problem "hard to make a structured planning" has several causes. First of all, the future demand is highly uncertain, since they have an Engineer-To-Order production approach. They only know what to produce once they have a project they can work on. Moreover, the amount of data that is usable is limited. The company does not have a ERP-system currently, and data is mostly collected from hour registration and machine output. Another cause is the outdated prediction tools for working hours. This prediction tool is often not accurate, which makes it hard to make a structure planning and it also makes the decisions of how much to outsource a lot harder.

The problem "hard to make a structured planning" has one final cause. Currently, Senro has no clear insight into the times modules, which is how they call a part of a project, are waiting in between different phases of production. The waiting time in this case is the time a module is not being processed during working hours. Multiple stakeholders mentioned that the modules are currently waiting quite long between production phases and that currently there is no clear insight into how long they are waiting exactly in between the phases.

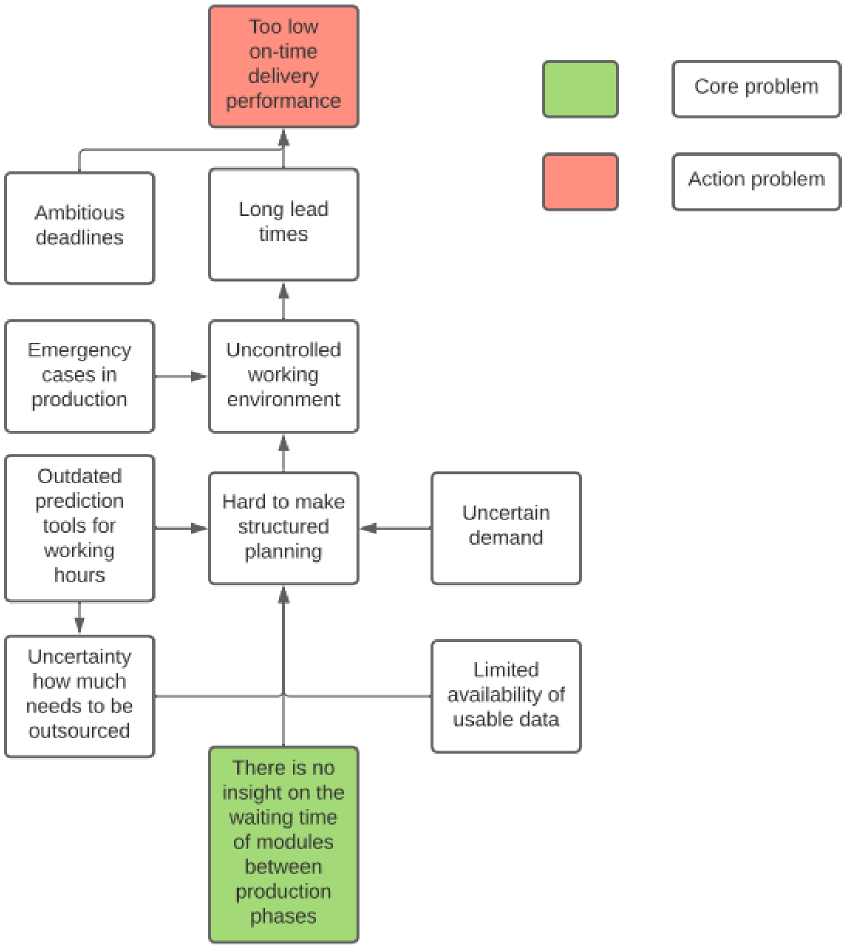

Figure 1.2: Problem cluster

1.2.3 Selection of core problem and research question

The next step is to look for a core problem to deal with. In order to choose the core problem the four rules of thumb as described in the *Solving Managerial Problems Systematically* book by Heerkens and van Winden (2017) are used:

1. There is a convincing relationship between problems
2. Problems with no direct cause themselves are possible core problems
3. If a problem cannot be influenced, it is not a core problem
4. If more than one core problem remains, choose the most important one

After following the rules of thumb, three core problems can be found in the problem cluster. The first one is "There is no insight on the waiting times of modules between production phases", the second core problem is "Outdated prediction tools for working hours" and the final core problem is "Limited availability of usable data". These are core problems since they can be influenced and have no direct cause themselves.

In order to make a decision between these core problems first the impacts of both were looked at and second the wish of the company was taken into account. This result in the following selection of the core problem: "There is no insight on the waiting times of modules between production phases". The problem was chosen, since Senro thinks that addressing this problem is the most likely to improve the on-time delivery performance compared to the other possible core problems. The goal of the assignment is to provide good insights in the current flow of modules between production phases and to come up with solutions on how to reduce these times. The waiting times also need to be reduced, since according to stakeholders they are too long, which in turn contributes to improving the on-time delivery performance. This core problem is measurable. In this research the waiting times will be measured in working days to exclude weekends and give a true representation of the time that modules are waiting. Now that the core problem is known, the main research question can be stated as follows:

"What are the causes of modules waiting between production phases at Senro and how can they be reduced?"

In order to solve the previously stated research question, knowledge questions have to be defined. Answering these knowledge questions gives the answer to the main research question. The knowledge questions have been formulated by following the seven steps of the managerial problem-solving method (MPSM), according to Heerkens & van Winden (2017). The knowledge questions are presented in this section and a more detailed explanation of these questions can be found in section 1.3.1.

1. What does the current production flow of modules look like in terms of time and routing and what are causes of waiting time?
2. What methods and theories are available on reducing the lead time in Engineer to Order (ETO) companies, focusing on waiting times in production?
3. What are solutions for reducing waiting times between production phases and which solution is the best?
4. How can the solution be implemented at Senro?

1.3 Research design

This section gives an outline for the research performed as well as presenting the intended deliverables.

1.3.1 Knowledge questions

To start of the research design, the type of research that is used in the bachelor assignment is explained for each of the knowledge questions. The knowledge questions are stated along with a more in-depth explanation and motivation. The following are the definitions of the different types of researches:

1. Descriptive study: An accurate profile of events, persons or situations is gained.
2. Exploratory study: Insights are gained about certain topics of interest.

3. Explanatory study: Causal relationships between variables is established
4. Evaluative study: Find out how well something works.

Knowledge question 1: **"***What does the current production flow of modules look like in terms of time and routing and what are causes of waiting time?"*

To start of the research, a good insight in the current production flow of the modules is needed. A descriptive study is done by answering this knowledge question, because an accurate profile of the situation is gained. Stakeholders are interviewed to gain a better insight into the current production process and how modules are flowing in terms of routing between different production phases. This also includes the waiting times of the modules. Stakeholders include the Operations Manager as well as employees working in the workshop. Furthermore, data analysis is done to identify how modules are flowing between different production phases in terms of time. A visual representation of the flow is given along with a timeline. In the timeline the waiting times can be seen. Then the causes of waiting times are identified. The answers to these are found by doing data analysis as well as by holding interviews with relevant stakeholders. The answer to this research question can be found in Chapter 2.

Knowledge question 2: **"***What methods and theories are available on reducing the lead time in Engineer to Order (ETO) companies, focusing on waiting times in production?"*

To find the theories and methods, which can help solve the core problem, a systematic literature review is done. This is an exploratory study, since new information and insights will be gotten about a certain topic. With this information a solution approach can be chosen and formulated in knowledge question 4. The literature review and answer to this knowledge question can be found in Chapter 3.

Knowledge question 3: ***"****What are solutions for reducing the waiting times between the different production phases at Senro and which solution is the best?"*

Explanatory study has to be done to answer this knowledge question. The impact and feasibility of different theories and methods needs to be found out. The main variable to measure is the waiting time between the production phases. This needs to shorten. The best solution in the end is most likely be the one that reduces the waiting time the most, but is also feasible. Different factors should be taken into account, such as the opinions of important stakeholders within the company. The approach for the chosen solution(s) is given. Evaluative study is also done when answering this knowledge question, since we will be finding out which solution works the best for the situation we have at hand. The way to determine the best solution is to make a weighted decision matrix in which we assess the solutions that were formulated in the previous knowledge question on a few relevant criteria. In Chapter 4, a Monte Carlo simulation is build. With the use of the Monte Carlo simulation model, this research question is answered in Chapter 5.

Knowledge question 4: ***"****How can the solution(s) be implemented at Senro?"*

In the final knowledge question the implementation of the solution is researched. This knowledge question is related to the sixth phase of the MPSM. This is done with an explanatory study. The stakeholders for this implementation plan are mostly the employees directly affected by it in the workplace , but also the employees responsible for the process in the office. The result of this is a qualitative plan, in clear language. The plan is supported by quantitative data. The answer to knowledge question 4 can be found in Chapter 6.

1.3.2 Key constructs and variables

The key variables of the research will be the following:

- Waiting times of modules between production phases: The waiting times between production phases are the main variable, as that is what the research aims to shorten.
- Lead times: Is the amount of time from the start of the process until the end. For the research the impact of waiting times on the lead times will be discussed. The lead times in this research are focused on the lead times in production.
- Utilization of departments: Relates to the percentage of the available time the employees in a department are working.
- Variability: Relates to lack of consistency, which can have an impact on waiting times as well.

1.3.3 Intended deliverables

This sub-section gives an overview of the deliverables that result from the thesis at Senro. The deliverables are the following:

- An extensive analysis of the current flows of modules between production phases.
- Theoretical framework on reducing waiting times in production in an engineer-to-order production environment
- An overview of possible solutions along with the arguments for the best solution(s).
- An implementation plan for the best solution(s) found for the problem. In this implementation plan the activities that need be done in order to implement the solution are described. Furthermore, this implementation plan needs to include numerical proof that the plan will improve the current situation and describe the cost of implementation.

2. Current production process

In this chapter the current production process of Senro is described. This chapter aims to answer the first knowledge question. One thing to note is that every time a day is mentioned in this research, we refer to a working day.

What does the current production flow of modules look like in terms of time and routing and what causes waiting times?

In Section 2.1 the current production process is described, in order to identify through what phases of production a modules needs to go before it is finished. In Section 2.2 a floor plan of the production is given, in which the routing of the modules can be identified. In Section 2.3 a performance measurement is done on the current production process. This measurement includes production lead time and more specific performance measurement on the different phases in the production. Afterwards, a conclusion can be made on the current production flow of modules in terms of time and routing. Then when the performance measurement of the current system is analyzed, causes of waiting times are identified in Section 2.4 This is split up in causes of waiting time per production phase and also causes that are applicable to the entire production process. Finally, in Section 2.5 we determine where the focus of this research is on.

Section 2.1 and Section 2.2 of this chapter are answered by doing qualitative study, mainly in the form of observation and by conducting interviews. Section 2.3 is answered by doing a data analysis in the information systems they have. Section 2.4 is mostly answered by doing interviews with important stakeholders within the company as well as by doing data analysis.

2.1 Pre-production and production process

In this section, first the pre-production process is explained generally, in order to get a better insight of the complete process going on at Senro. after that this section will go more in-depth on the production process, since that is the scope of this research.

The pre-production workflow can be seen in Figure 2.1. This workflow is simplified, since it is a very complicated process due to the Engineer-to-Order nature of the company and it is not in the scope of the research. It is however good to provide this workflow, to get a better context of the entire process a project goes through. Only the main parts of the phases before the production are given, to increase the understanding of the context of the process at Senro. The pre-production phase starts with a customer order, requesting a very specific type of product. This is discussed with Senro and a lay-out drawing is made that needs approval from the customer. When the customer is satisfied with the initial drawing, negotiations about the price and the delivery date take place. The engineering department then goes on to draw the project in 3D, which is needed to start the production. The finished 3D drawings are then checked and cutting programs are made by the work preparation department.

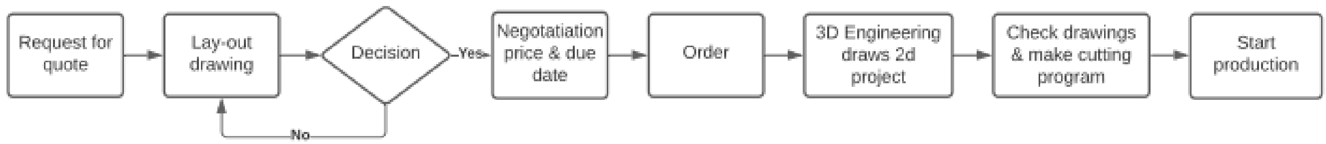

Figure 2.1: Simplified version pre-production process

Now it is time to describe the production process. The general process of the production can be seen in Figure 2.2. After the pre-production phase is finished, the production phase can be started. The first phase of production is the laser cutting machine. The laser cutter has received cutting programs that were made by the work preparation department. Raw materials have been procured and are stored in the storage rack in front of the laser cutters. The operator at the laser cutter checks these programs on correct- and completeness. The plate steel is then cut with high accuracy and after that unpacked by the operator and stored temporarily in a different storage rack before it gets to the next phase in the production.

When the plate steel is cut and unpacked by the laser operator, it is time to bend the plates if the plates do not get outsourced. The bending machine is operated by two employees. These employees gather the plates they need to bend and set up the bending machine. The plates that need to be bend have different sizes and thicknesses, which needs to be set up in the bending machine.

After plate steel is cut and bent, it reaches the welding department of Senro. In this department, the plate steel joins the profile steel. Profile does not need to be cut or bent in the previous two production phases. Profile steel is sawn at the welding department. Then the modules are drilled and welded in the welding department. The welding department consists out of nine welders, although the amount of welders present at a time differs a lot. After the welding is finished, the modules need to be ready for transport, to go to the next phase.

The coating phase that comes in between welding and assembly is not done at Senro. The modules need to be coated/painted, in order to increase the lifespan of the materials. The materials will be exposed to different kinds of weather conditions and by coating them they decay less quickly. Senro currently outsources coating this has several reasons. If Senro wants to do more coating internally, they need more space and the right employees, which they do not have. Licenses are also required for coating. This combined makes it hard to do coating internally and that is why they outsource this phase in production. The coating phase is included in the lead time, however the time it takes to do phase is fixed (in this research).

After the modules are coated, they are transported back to Senro to go to the final production phase: assembly. In this phase, the parts of the modules are assembled. Assembly is done manually at Senro. Due to the fact that every module is different, it is almost impossible to automate parts of the assembly. After the modules have been assembled, they are made ready for transport to go to the construction site. This phase is therefore the last production phase discussed in this research.

Figure 2.2: Production phases

2.2 Facility layout and routing of modules

To visualize the flow of modules, a floor plan of the workshop is given in this section. This will be done by splitting the floor plan up into the 2 halls it consists of: The assembly hall and the welding hall. We start off with the assembly hall, which is where modules start and end. Then we continue to the welding hall, where modules go before they are outsourced to a coater. Then at the end of this section the floorplans of these 2 halls are combined to make a total overview of the facility layout and routing of modules within this layout.

First of all we dive deeper into the floor plan of the assembly hall as can be seen in Figure 2.3. The modules enter in the right bottom of the floor plan.. They are then stored temporarily before they are put through the laser cutter in the red area called “Storage laser”. The cut plates are then unpacked by the laser operator and stored temporarily in the orange area called “storage bend”, before the bending machine operators gather them for bending. After the modules are welded and coated externally, they return to the assembly hall in the top left of the green area in Figure 2.3. The “materials for assembly” in Figure 2.3, represent materials that have been insourced that are needed for assembly. “Loads” & “Truck loads” represent materials that are stored temporarily after they come back from the coating company. There is no fixed spot for truck loads that are not ready to go in assembly yet. The movement the modules do in the assembly hall is never the same, however for simplicity it is assumed that they follow the U shape movement as represented in Figure 2.3. After assembly they are ready for transport and they exit the assembly hall.

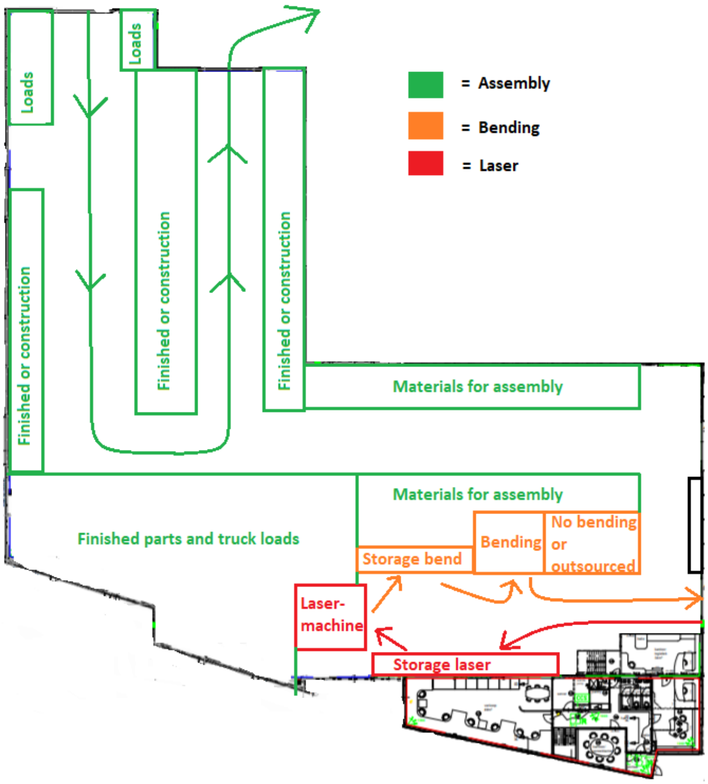

Figure 2.3: Floorplan assembly hall

After the modules have been cut and bent, they go to the welding hall. The routing the products do in the welding hall can be seen in Figure 2.4. The work enters the hall and goes to one of the welding spots or is stored temporarily. After that the modules leaves at the top of the welding hall to go to the coater.

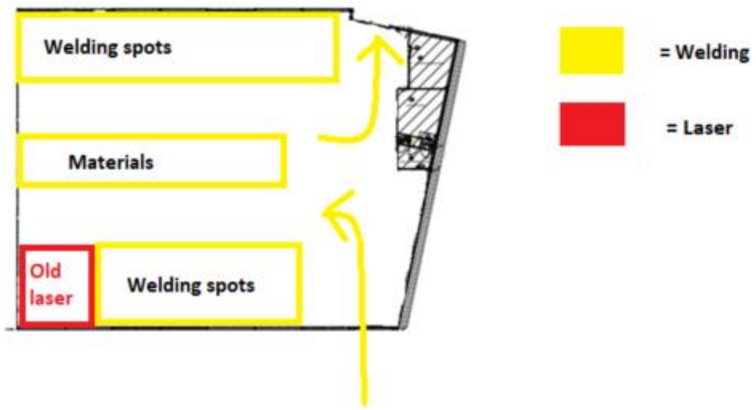

Figure 2.4: Floorplan welding hall

2.3 Performance measurement

Now it is known how the products flow through the different production phases in terms of routing, it is time to look at the performance of the production process. In this chapter we look at the production lead times of modules, processing time per production phase on module level. In this chapter values are presented and in the next chapter we go more into a more in-depth analysis of these values to determine to what extent these values are justified. We obtain the data in this section from the MySQL database Senro has. In this section the following performance measurements are provided:

- Production lead time: The total time from start of production at the laser cutter, until the end of production where the module is assembled. The value for production lead time is the entire length of the timeline made at the end of this section.
- Processing times per production phase: total time a module is processed per production phase.
- Time present in production phase: Represents the total time in working days it takes an entire module to get through a phase in production. This is needed to make the timeline at the end of this section.
- Average start time of production phase: This measurements is the average starting time for a certain production phase in working days after the production has started.
- Waiting times of modules between production phases: This performance measurement is the most important of this research, since we aim to identify this and eventually reduce this.

Production lead time

The production lead time is the time it takes for a module to enter the laser cutting phase until the end of the assembly phase. This is the entire time the module is in production. As stated in Section 1.2.3 the company ideally wants to have an average lead time of 21 working days for the production. We need to know what the lead times currently are, since they have no insight in that performance.

In order to explain how the lead time is calculated in this research and to explain how a project consists out of a certain number of modules, we first zoom in on one project. First the production lead times of individual modules within a project (P2018-034) are presented in Figure 2.5. In this figure the production lead times for all modules in that project are presented in a bar chart, the chart also includes a line for the average lead time. As can be seen in the bar chart, the average line is just under 30 working days (29.24 to be exact). This is longer than the lead time of 21 days that is desired. Project P2018-034 as seen in Figure 2.5 was chosen, since it is one of the largest projects in terms of working hours in the last years. The production lead time was calculated by determining the amount of weekdays there are between the first date a module was worked on in production and the last day it was worked on in the assembly phase.

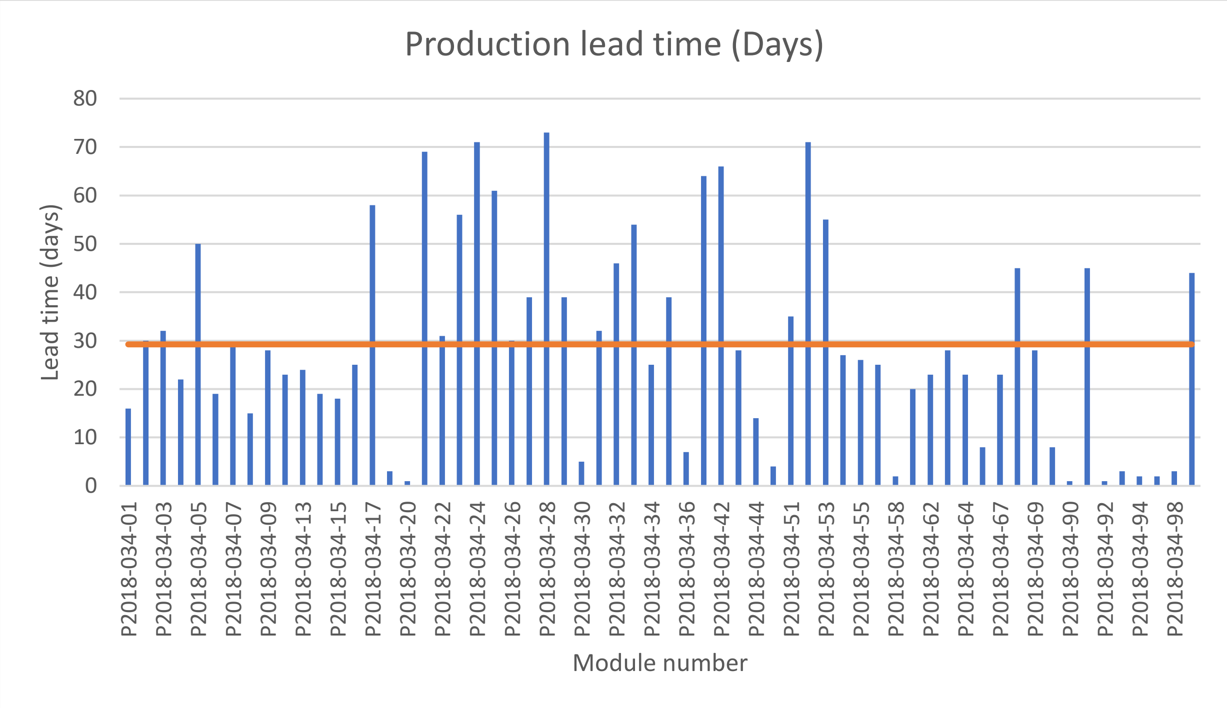

Figure 2.5: Production lead time project P2018-034

Now it is explained how we obtain the values for lead time, we apply this to more projects to get a more realistic representation of reality. Projects which were worked on for more than 5000 hours in total and started after the year 2017 are chosen for this analysis, since these are the bigger projects Senro has done. Having over 5000 hours worked on results in more data. Before 2018, the data was not tracked in the same way as after the 1st of January 2018. That is why a criteria for choosing projects to analyze is also to have a start date on or later than 01-01-2018. Another reason for choosing these bigger projects, is that these projects are processed a lot more time in the production process and are present in the process for much longer, meaning that there is more data available to base this research on. Taking the restrictions into account we select the 7 projects (including P2018-034) as can be seen in Table 2.1.

Table 2.1: Seven largest relevant projects between 2018-2020

Project name	P2019-068	P2020-113	P2018-034	P2020-048	P2019-040	P2019-045	P2018-173
SUM TIME (HOURS)	20220.31	10984.50	10674.09	6568.79	5850.19	5248.83	5080.99

The average lead time for each of those 7 projects can be seen in Figure 2.6. As can be seen in the figure, the lead time for P2019-068 is significantly longer than the rest of the lead times. This project is also almost twice as big as any other project. The long lead time may therefore be caused by the fact that the modules were very large. The average lead time for all modules over these 7 projects, is 29.36 working days with a standard deviation of 4.96 days. These 29.36 days are all working days, since the production is not active in the weekends, apart from some exceptions that will not be included in this research. This is 8.36 workings longer than Senro wants ideally. We conclude this from the fact that Senro ideally wants the production process to take 21 days on average. This is a reduction of 28.5% of the production lead time. That is quite a big difference, and that is why further on in this chapter we want to find out what causes of waiting time are and further on in the research we discuss how to reduce them.

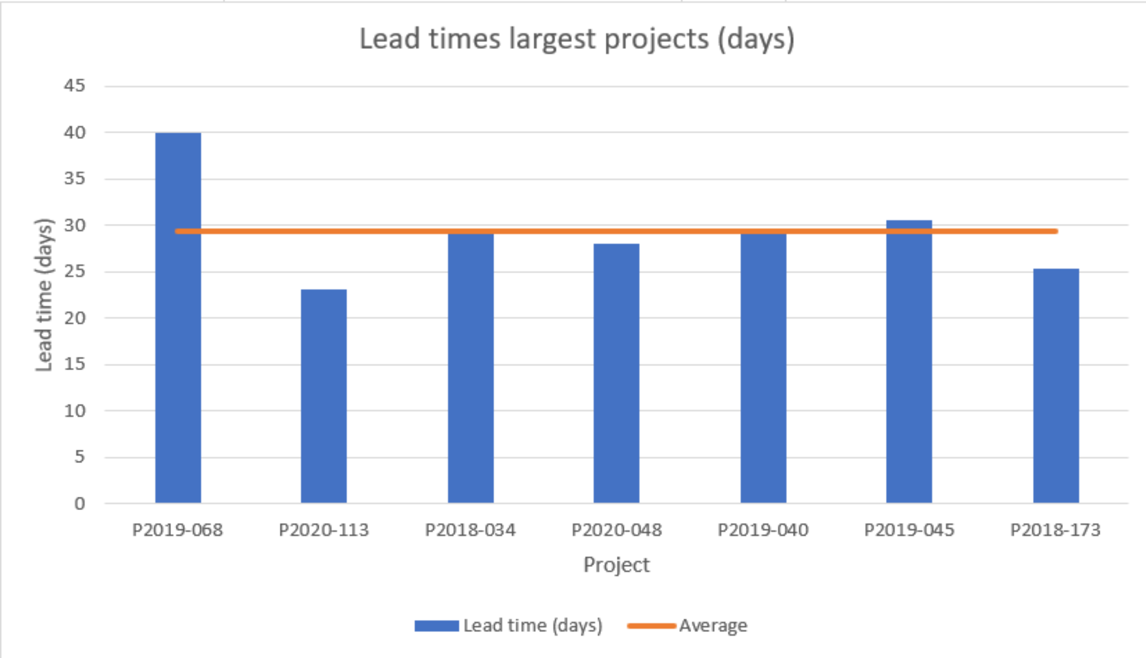

Figure 2.6: Average lead time per module for different projects

Processing time per production phase

Now that the lead times for the seven selected projects between 2018-2020 are known. It is time to determine the average processing time for each of the modules in these projects. If these processing times are also known, a ratio can be calculated for the time a module is processed compared to the total lead time.

In Table 2.2, the average processing time per module for the different phases in the production can be seen for these seven largest projects. As can be seen in the table, the welding and assembly phase take the most time by far. The processing time varies quite a lot in reality, since every module or parts is different. However, due to the limited database of the company it is not possible to categorize these modules effectively. That is the reason for taking averages. The welding department takes the most hours, the laser cutting takes the least time as seen in Table 2.2. What can also be seen is that the standard deviation for processing times seem quite high, this will be discussed more in-depth in Chapter 2.4.

Table 2.2: Average processing time per module per production phase

Production phase	**Total modules**	**Total time (hours)**	**AVG processing time per module (hours)**	**Standard deviation**
Laser cutting	283	2251.98	7.96	9.62
Bending	257	2452.77	9.54	12.06
Welding	270	14323. 28	53.05	70.50
Assembly	219	8561.71	39.09	52.40
Total processing time per module during lead time			109.65	
Ratio - processing time : lead time			0.48	

Time present in a production phase

It is now known that welding and assembly take the most time, but there are also more employees working in those departments. This is also what skews the ratio of processing time versus lead time. Therefore we also take a look at the total time a module spends on average in a certain phase in the production. This represents the time the entire module starts a production phase until the final piece of the module is finished at the phase. This will be determined after determining the total time a module is in a certain phase. In Table 2.3, the average time in days a module is at a certain phase is noted. This is calculated by subtracting the first time someone worked on a certain module at that phase from the last time someone worked on it.

Table 2.3: Average working days present at a phase for a module

Phase	**Time present in phase (days)**	**Standard deviation (days)**
Laser cutting	2.43	0.64
Bending	2.38	0.75
Welding	6.07	1.08
Coating (externally)	5	0
Assembly	5.17	1.63
Total time in phases	21.05	

In order to make a timeline, we need to know the average starting time of a production phase after the production process is initiated. The laser cutting phase starts at zero days, since that is the starting point for the production in this research. The assembly phase represents the final phase of the production lead time. So the last 5.17 days of the 29.36 production lead time represents the assembly phase. The time a phase is entered after production is started, can be seen in Table 2.4. The reason that the gap between the start of welding and the start of assembly is that big has to do with the fact that the modules have to be coated externally. Still, there is room there for improvement, this is analyzed in the next chapters.

Table 2.4: Average start time of a production phase after production starts

Phase	Time from start until phase is entered (days)	Standard deviation (days)
Laser cutting	0	0
Bending	4.09	0.81
Welding	6.59	1.45
Assembly	24.19	2.19

Waiting times

The most important performance indicator of this research is waiting times of modules between production phases. This is the most important KPI, since it is the one that is attempted to reduce in this research. The waiting time in this research is defined as the time a module is in between two different production phases. In reality there is also some other waiting time of a module when it has entered a production phase, but that is not taken in the scope of this research. The waiting times between production phases are calculated using the values in Table 2.3 and Table 2.4. In those two tables, we can see when a module enters a phase on average and how many days the module is at that phase on average. Based on this we construct the timeline in Figure 2.7, from which we can derive the waiting time between production phases.

Table 2.5: Waiting times between phases in production

	Waiting time of modules between phases (days)
Waiting time between production phases	
Laser cutting - Bending	1.66
Bending - Welding	0,12
Welding - Assembly	6.53
Total	8.31

In the table it can be seen that the time an entire module is waiting is the largest between the welding and the assembly phase. The total time it takes to reach assembly from welding is 11.53 days, however the module is painted for 5 days in this time. That makes the total waiting time 6.53 days between welding and assembly.

Timeline

The lead times, the time spent at a production phase, the waiting times and the starting point of a production phase are now known. An average timeline can now be set up. In this way we visualize the flow of production by combining all of the values on lead times, processing times and waiting times. As calculated before, the total production lead time is 29.36 days. Therefore, the total length of the timeline is 29.36 days. In the timeline also the total processing periods for the modules are included. There is also be space between the production phases. This is time the entire module is waiting. There is also time within the processing periods where parts of the module are waiting. In Figure 2.7, the timeline of an average module can be seen.

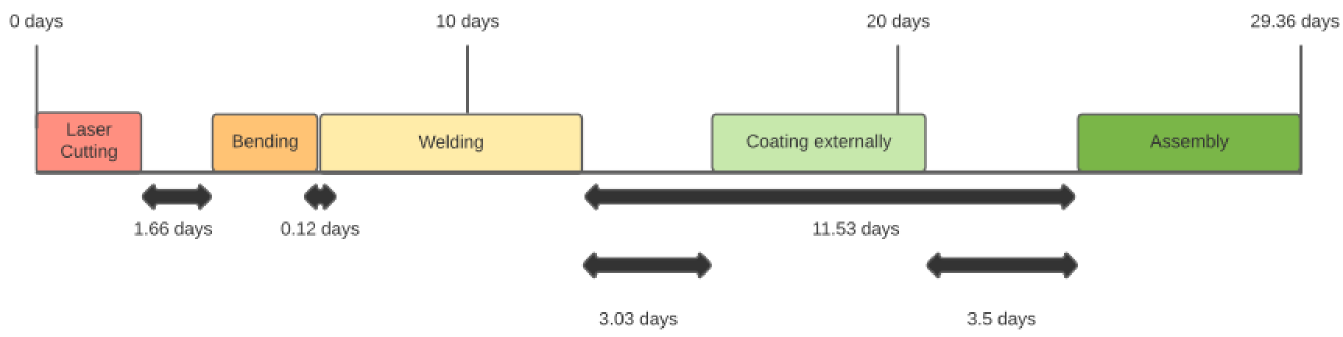

Figure 2.7: Timeline of a module on average in working days

2.4 Causes of waiting time at Senro

In this section, the causes of waiting time at Senro are identified. In the previous section we determined waiting times between production phases. In this section we go more in-depth in these numbers. First we find out what the causes of waiting time can be derived from the database by doing data analysis. We then go on the determine the causes of waiting time that could be derived from interviews and/or conversations with employees of Senro.

2.4.1 Causes of waiting time following from data analysis.

In the previous chapter, we determined the total time a module was present at a certain phase, how long it was processed for and how long the time was between the previous phase. In this section we identify the causes of waiting time by looking at the following three factors:

- Variability
- Utilization
- Realized man hours versus predicted man hours

Utilization and variability are discussed at the start of this section, since they have a massive impact on waiting time according to Hop & Spearman (2008). In the literature review in chapter three we go more in-depth into the effect of utilization and variability. At the end of this sub-section, the realized versus predicted man hours is discussed, since this is an indication of how well Senro can estimate how long a job is going to take.

Variability

The variability of a module for the different production phases can have an impact on the waiting time between the production phases. According to Hopp & Spearman (2008) a reasonable relative measure of the variability is the standard deviation divided by the mean, called the coefficient of variation (CV). The higher the value for CV, the higher the waiting times are expected to be, this will be discussed in more detail in Chapter 3. In Table 2.6, the classes of variability can be seen as given by Hopp & Spearman (2008) for different CV values. Based on this figure, we can determine in which variability class the different production phases fall in terms of processing times. The other type of variability as discussed in Chapter 3.2, namely arrival variability, is calculated in Chapter 4. The values for arrival variability we found were 0.43 for welding and 0.69 for assembly. This means arrival variability is in the low variability class for both of these departments.

Table 2.6: Classes of variability by Hopp & Spearman (2008)

Variability class	Coefficient of variation	Typical situation
Low (LV)	$c < 0.75$	Process without outages
Moderate (MV)	$0.75 \leq c < 1.33$	Process times with short adjustments (e.g setups)
High (HV)	$c \geq 1.33$	Process times with long outages (e.g failures)

The values for the CV for the different production phases can be seen in Table 2.7. The CV values for laser and the bending phase are moderate, whereas the CV values for processing times for welding and assembly are in the high variability class. Even though laser and bending fall in the moderate class, they are high in this class. This means that the CV is quite high for all production phases in terms of processing times. This is also explained by the fact that Senro has an Engineer-to-Order production approach, meaning that all projects they do are completely different. We can therefore not be surprised by the (high) value of CV. This "strategic variability" is used to get a competitive advantage, therefore it is not necessarily bad to have a high variability. We can however raise questions about the extent to which this variation is justified.

Table 2.7: CV for processing times per production phase

Phase	AVG processing time	Stdev	Coefficient of variation (CV)	Class
Laser	7.96	9.62	1.21	Moderate
Bending	9.54	12.06	1.26	Moderate
Welding	53.05	70.50	1.33	High
Assembly	39.09	52.40	1.34	High

Utilization

The utilization of a workstation or in this case production phase has tremendous impact on the waiting times in production as is explained in Chapter 3. That is why the utilization of the different production phases need to be determined. The utilization values are almost impossible to determine in the current situation, however Senro currently tries to use as much capacity as possible. The laser cutter is the only phase assumed to have some capacity left. In Chapter 4, we build a Monte Carlo simulation model for the welding and assembly department from which we can determine the utilization levels. The utilization levels were 0.92 for the welding department and 0.86 for the assembly department.

Realized man hours vs predicted man hours

The pre-calculation for man hours needed are compared to the realized man hours. The reason this is done, it that this is a good indicator of the insight planners at the company have about their production process. If the hours it takes to complete a certain production phase can be predicted accurately, a better planning can be made, resulting in less waiting time. Furthermore, if producing takes more time extra costs are made by the company that are probably not included in the offer made to the customer. In Table 2.8, the difference between the pre-calculation and after-calculation for man hours needed can be seen for the projects discussed earlier in this Chapter.

Table 2.8: Pre-calculation of man hours needed vs after-calculation

Phase	Total PC (hours)	Total realized (hours)	Difference
Laser	2549.73	2447.41	-4.01%
Bending	310.69	2741.75	-8.93%
Welding	15983.45	15792.75	-1.19%
Assembly	8505.73	11137.72	30.94%

The prediction for the first three production phases at Senro are very decent. Bending takes 8.93% less time than is expected, which is not really a problem. The problem that can be derived from Table 2.8 is that assembly takes on average 30.94% hours more than predicted before starting. This is quite a big difference. This can really mess with the planning and negatively impact the overall profit the company makes. Because this phase takes longer than planned the waiting time before starting can be longer.

2.4.2 Causes of waiting times following from interviews

In this section, we discuss causes of waiting time that relate more to the entire production process. This are more general things that happen or have an effect on more phases in the production. The findings in this sections are mostly based on interviews or conversations with employees.

- **Pre-production delays**
  There are some causes of waiting times that happen before the production starts. Awaiting materials is a pre-production delay, since you can for example not start laser cutting when the sheets of metal have not arrived yet. Another pre-production delay that happens occasionally at Senro is the engineering phase taking longer than expected. Of course, when the drawings are not finished yet, it is impossible to start with production.
- **Incorrect drawings**
  Drawings are made by people and unfortunately it is unavoidable that mistakes are made on these drawings. Mistakes cost a lot of time in production as it needs to go back to engineering to identify and fix the mistake. This can take several days, depending on the priority that module has in production. When a mistake is only noticed at the assembly phase even more time is lost then when the mistakes is identified before laser cutting. Time and money is lost when the mistake is identified at assembly, since a module has then already gone through three production phases. More mistakes in drawings can be caused by a busy schedule, since then there is more pressure to work fast.
- **Emergency orders in production**
  An urgent order can be defined as an order that flows faster through production than a regular order. Urgent orders in production are sometimes necessary. A certain delivery date has to be met, or there is an issue at a customer that needs to be fixed immediately. These urgent orders have a massive impact on the organization, since all work that is currently being done has to be dropped in order to work on the order with the higher priority. This causes other orders to get a higher lead time , which can also have an impact on whether the delivery date for those items is met depending on the slack they have. Usually the consequences of urgent orders are bigger in an organization where the utilization levels are higher. Furthermore, urgent orders increase the uncontrollability in the organization. The cause of them differs, but are mostly the result of delivery dates that were ambitious from the beginning or problems at a customers have to be solved immediately.
- **Missing parts in production**

When a production phase needs to be completed, all parts that are necessary should be present. If parts are missing this causes waiting time for a module, since you can simply not start. This happens at Senro as well, especially at the assembling phase. Employees say that most time get lost, because some small parts are missing like bolts and nuts. Currently Senro keeps some 'up-for-grabs stock', which consists out of materials or parts that are used frequently and kept as a buffer for mistakes. Still some parts are missing, which usually happens with parts that are used less frequently. However, this is not only related to what Senro keeps in stock. Suppliers for certain materials can take longer to deliver than what would be ideal to keep flow in production going. This can be caused by delay at the supplier or because the supplier is simply not given enough time.

- **Work outsourced to Senro**
  Senro outsources work to other companies when they do not have enough capacity to produce the amount that they need to produce. However, sometimes they also take on work other companies outsource to them. This work takes time away that could be used to produce your own projects, causing modules to wait. This can disturb your own process, and there are doubts whether doing this is worth the money it yields. It can however provide some non-monetary advantages like having a better connection to other companies. This way when Senro needs help in the future they are more likely to be helped by the companies they have previously done some work for.
- **Limited availability of usable data**
  The company currently does not have an ERP-system as mentioned earlier in this research, though they are working on this. This means that orders are not tracked as well as it could or should be. This decreases the insight into their own processes at Senro. This influences decision making in a negative way. Planning is done on gut feeling and decisions on how much to outsource are based on simple calculations and previous experiences. This unavoidably leads to mistakes, causing disruptions and therefore waiting times in production.
- **Employees not working structurally**
  This research is not focused on the human aspects of the production, however it should be mentioned that working habits differ between employees. When an employee works in a very structured way, the processing times for jobs will have less dysfunctional variability. Standardized working ways will reduce this variability and therefore the waiting times in production, the reason for this is discussed in more detail in the next Chapter.
- **Mechanics unavailable**
  When a product Senro has delivered to a customer breaks down and needs to fixed, they send mechanics from the assembly hall. This way the assembling department sometimes misses some employees, which reduces the total work that can be done there. Modules have to wait longer before it is their turn to be assembled.
- **Buffers in production**
  Buffers before production phases also contribute to waiting time. At Senro they want to have at least 1 to 2 days of work as a buffer for the welding department. This is done, because they do not want the welders to run out of work when the bending machine has issues or due to any other reasons. Nine welders are currently employed, so when welding has no work to do, that costs lots of money.
- **Transport to external coater**
  The time the modules are painted at an external company is fixed in this research and taken into account. The transport to go to this external company also causes waiting times. Welded modules are not transported daily, but only go to the external company when there are

enough materials to make the transport cost effective. This means that after modules are welded it can occasionally take a few days before they go to the painter. The amount of times loads of trucks are sent to the coater is dependent on a few factors. For example, currently most of the modules require to be galvanized, which is done at a different place compared to the places where coating is done. This means that trucks for 'normal' coating do not fill as quickly now, causing modules to wait longer. Senro does not send a truck to the coater when it is only 30% filled, since this is not cost effective at all.

2.5 Focus of research

In this section, we narrow down the research, which is needed to provide better and more accurate solutions in the end. We narrow down based on the information that is gotten in the first four sections of this chapter. From the analyses earlier on in this chapter, we can determine the problematic phases in production.

The focus in this research will be on the welding and assembly department. These two are chosen for the following reasons:

- *Highest coefficients of variation (CV):* The CV value for processing time per module are the highest in the welding and assembly phase. In theory this means that the waiting times are also likely to be higher in front of these
- *High utilization levels at these departments:* The utilization levels at these department are high according to multiple stakeholders. This contributes to waiting time, as will become clear in Chapter 3.
- *Longest waiting time between welding and assembly:* The waiting time between welding and assembly is the highest. Even when you take into account that the modules are painted externally in between these phases. This is the primary reason for focusing on assembly, since this research aims to shorten the waiting time between production phases.
- *Multiple waiting time causes related to assembly department:* The multiple causes of waiting time as determined in the previous section can be related to the assembly department.
- *Best data available for these departments:* For these two departments the data that is available is the best. For laser cutting and bending the data is as useful. That is a more practical reason for choosing the welding and the assembly departments.

2.6 Conclusion

In this chapter the first knowledge question of this thesis has been answered. The current production flow of modules is described in terms of time and routing. We found that the average production lead time is 29.36 working days, which is 8.36 working days more than the 21 workings days Senro wants it to be. The total waiting time of entire modules between production phases is 8.31 working days. This means that it is literally impossible to reach the norm of production lead time by just trying to reduce the waiting times between production phases on module level. However, this does not mean that there is not room for improvement. We then found the average time a module spends at all phases in the production, as well as the average start time of the different production phases. With these measurements we were able to construct a timeline as shown in Figure 2.7. This timeline combines a lot of information and presents that in a clear and concise way. After that, the causes of waiting times were determined by first splitting it up in variability for processing time, utilization levels and pre-calculation versus after-calculation for all four production phases. After that, causing of waiting times that were derived from conversations with employees were described. This resulted in a lot of different causes of waiting times, which is also somewhat expected in the complex Engineer-to-order production environment Senro is producing products in. The focus of the research is set on the welding and assembly department.

3. Literature review

The current situation has been analyzed and therefore it is time to do a literature review on what causes waiting time and how to reduce the waiting time. For each theory or method found, it is also described what the relevance in this research is. This chapter aims to find an answer to the third knowledge question:

What methods and theories are available on reducing the lead time in engineer-to-order (ETO) companies, focusing on waiting time in production?

This chapter starts with theoretical causes of waiting times before moving on to the quick-response manufacturing (QRM) theory and approach to waiting times in Section 3.2. Then Section 3.3 discusses the relevant items for this research on waiting times and how to reduce them. From these theories, the elements that are applicable to my research and can provide solutions are discussed in the conclusion in Section 3.4.

3.1 Theoretical causes of waiting time

In order to get a better understanding of what causes of waiting time at Senro are, first off literature study is done on potential causes of waiting time and challenges of companies with an Engineer-to-Order (ETO) production approach. To start off this section, we go into more depth of what an ETO production approach entails and what challenges of ETO companies are. Afterwards, the theoretical causes of waiting times in production processes are researched.

Challenges of Engineer-to-order production approach

The wide variety of products causes companies to adopt different manufacturing strategies. These strategies can be categorized into four different categories with a different customer order decoupling point (CODP): make-to-stock (MTS), assemble-to-order (ATO), make-to-order (MTO) and engineer-to-order (ETO). The CODP is defined as the point in the value chain of products, where the product is linked to a specific customer order (Olhager, 2010). The following Figure from Sharman in 1984 depicts the CODP for all of the four different CODP's:

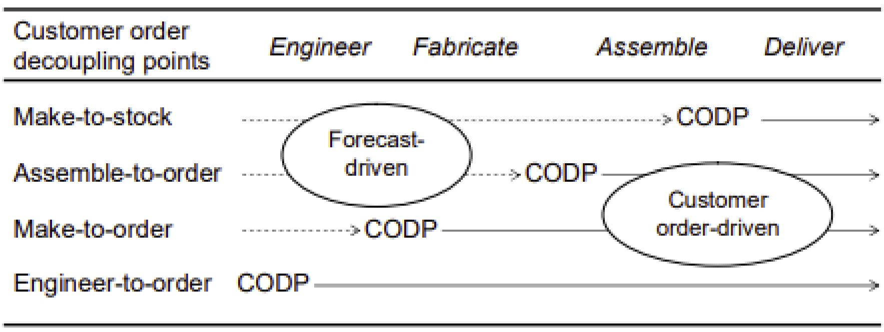

Figure 3.1: CODP for different manufacturing strategies (Sharman, 1984)

With the ETO production approach, the CODP is already at the start of the whole design- and production process. This means that ETO companies (such as Senro) deliver products that are tailored to fit the customers unique environment (Amrani et al., 2010). Figure 3.2 shows there are different levels of customization within companies with different companies.

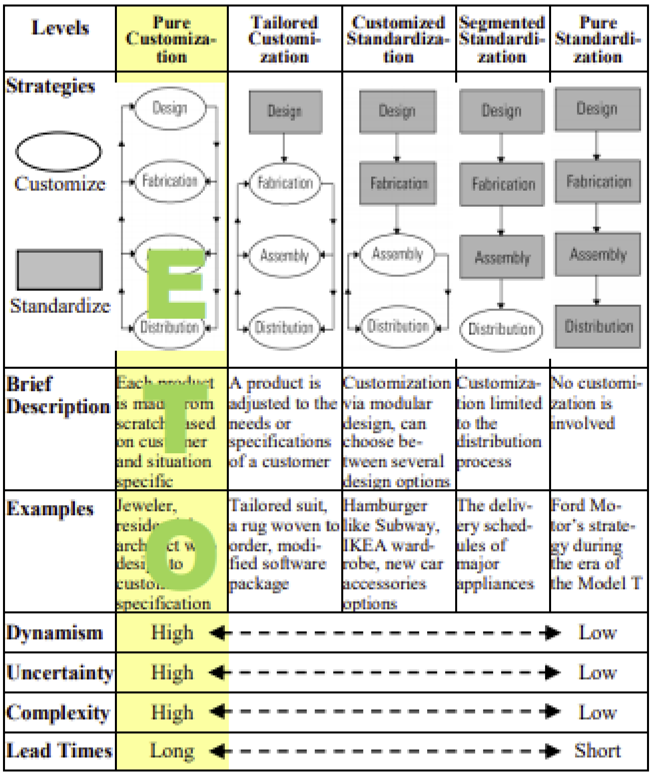

Figure 3.2: Levels of customization (Siong et al., 2018)

In ETO companies uses pure customization, which causes the dynamism of the company to be high along with uncertainty and complexity. Furthermore, lead times are long in these type of companies. The demand is unpredictable and production specifications of future orders is unknown.

The overall low degree of predictability in ETO companies, causes some of the following problems that lower the lead time performance and therefore increase waiting times at a company (New, 1977):

- Pre-production delays: This is seen when problems occur with pre-production delays on some batches (like awaiting materials).
- Sequencing problem: Lack of control in sequencing of jobs.
- Shop floor overload: More orders are accepted than can be handled. The overloaded orders are kept outside the shop or queue in front of high loaded equipment.

Waiting time is the time where a module is not being processed. According to Hopp & Spearman (2011), two factors contribute to long waiting times: high utilization levels and high levels of variability.

- **High utilization levels**

Work-in-progress (WIP), expected waiting time and expected processing time all increase in a system that is more highly loaded. For a given utilization, slower machines causes more waiting times. In the formulas for work-in-progress as given by Hopp & Spearman, congestion explodes as u gets to one, or in other words, if utilization gets to 100% (Hopp & Spearman, 2008).

- **High levels of variability**

Variability is very important in production to get a short cycle time and low WIP. The ability to measure, understand and manage variability is very important in managing the manufacturing process. The formal definition of variability is *quality of nonuniformity of a class of entities*. Or in more informal language: a lack of consistency or fixed pattern. The most prevalent sources of variability in manufacturing according to Hopp & Spearman are the following:

- “Natural” variability, including minor fluctuations in process time due to differences in operators, machines and material.
- Random outages
- Setups
- Operator availability
- Rework

Waiting waste is also part of Lean Manufacturing. In lean, waiting waste is inventory that is idle, whether it is between production phases or waiting on shelves to be demanded. Typical causes of waiting time include the following according to Lachance (2018):

- Unplanned downtime
- Production bottlenecks and not balanced production workloads
- Too long setup times
- Not enough people
- People out unexpectedly
- Poor quality
- Ineffective internal communication.

3.2 Quick-Response Manufacturing (QRM)

This entire section is based on the book “It’s About Time” by Rajan Suri (2010). This theory is used in this research, since the company is interested in the effect QRM could have on their production process. Quick-response manufacturing (QRM) is a companywide strategy developed for reducing the lead times in all aspects of an organization both internally as externally. QRM is mostly effective for companies that have high-mix, low-volume or full customization production environment. Most managers understand that reacting quickly gives advantage over competitors, however there are a lot of misconceptions on how lead times and therefore response time can be improved (Suri, 2010). QRM is built on the following four core concepts:

- The power of time
- Organizational structure
- System dynamics
- Company-wide implementation

QRM is different to the traditional approach. The traditional belief is: “Everyone needs to work faster, harder and longer in order to get the work done in less time”. The QRM principle is as follows: “Find new ways of completing the job, with a primary focus on lead time reduction”.

To visualize this, Figure 3.3 shows the progress of an order through a unnamed company. It shows a total lead time of 34 days. This figure also shows the ‘touch time’ in gray , which is the time an order is actually being processed. The rest of the time is the ‘white space’, where nothing is happening to the job. Traditional approaches focuses on reducing the touch time as this direct labor costs the most, whereas QRM focuses on reducing the total elapsed lead time.

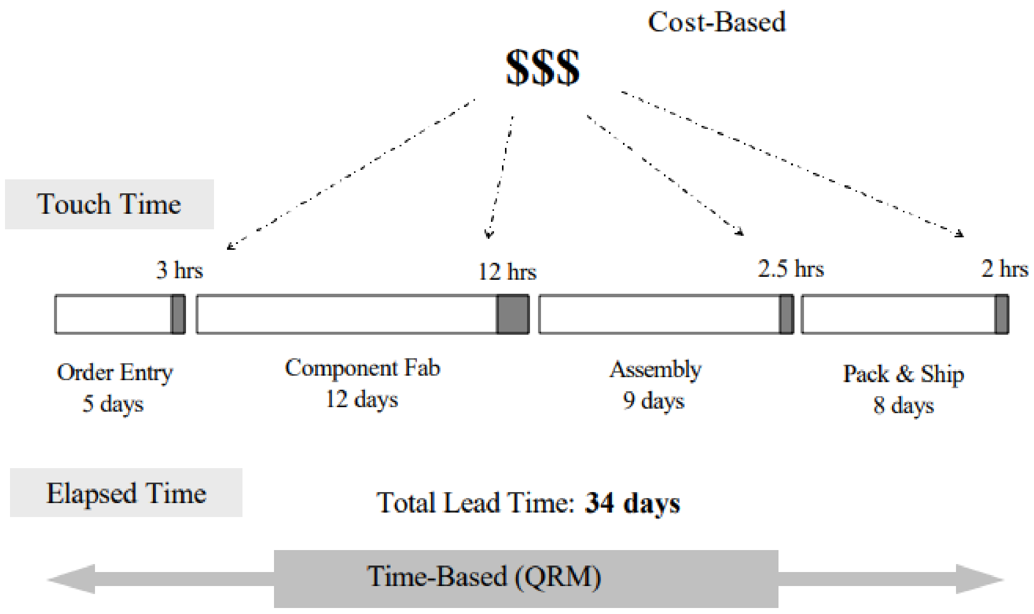

Figure 3.3: Comparison of cost-based vs time based (QRM) (Suri, 2010)

3.2.1 Manufacturing Critical-Path Time (MCT)

The QRM-strategy has developed a measuring method for the lead time called Manufacturing Critical-Path Time (MCT). MCT is defined as: "Time captured in calendar days starting from customer order, following the critical path, until the delivery of this order to the customer" (Suri, 2010). MCT is about highlighting the possibilities for improvement, not focusing that much on details. It is in calendar time, so not only focused on working days of the company. For calculating the MCT, three important rules hold (Suri, 2010):

- Assume that all activities are completed from the stretch
- Include queuing, delays that orders have, not the values for rush orders.
- Time spent in all stages by materials have to be added to the MCT map

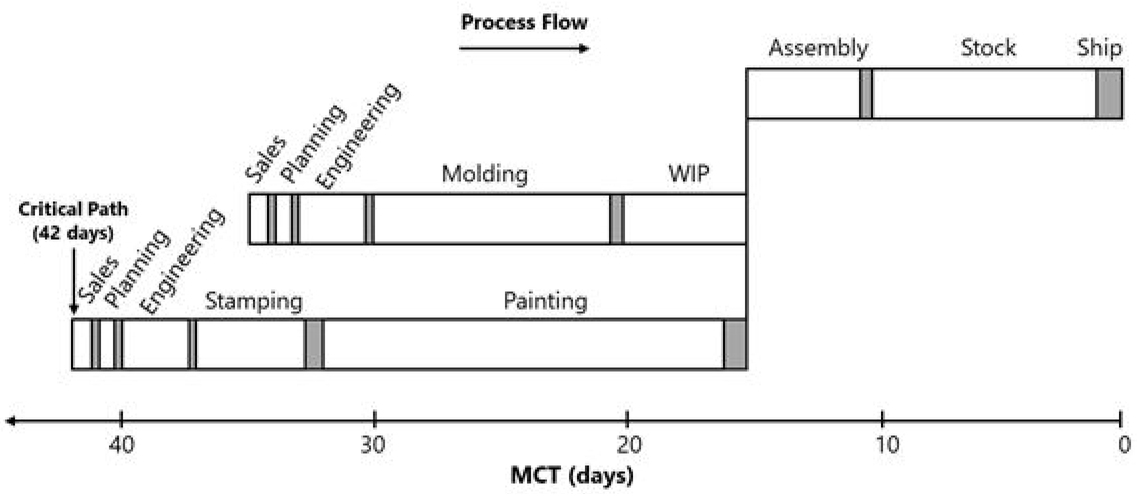

Figure 3.4: Example of MCT map (Suri, A Timely Metric, 2015)

The timeline made in Chapter 2 is very close to a manufacturing critical-path time. That is why in this research that timeline is used to highlight possible improvements. To measure improvement, QRM also developed a measuring unit called the QRM-number. The QRM-number is calculated with as depicted in Equation 1. QRM has several arguments for measuring improvement like depicted in Equation 1. The first reason is that improvement is usually associated with a rising line in a graph, MCT days reduction does not show this. The second reason for using this formula is that it shows relative improvement. The final reason for using the QRM-unit is that it makes it easier to compare the improvement of different cells with different MCT lengths in the base period.

$$QRM - Number = \frac{MCT\ base\ period}{MCT\ current\ periode} \times 100 \quad (1)$$

3.2.2 How QRM calculates waiting time

QRM uses Equation 2 to calculate waiting time. In this section the variables in the formula are explained, which gives a good impression on what the influence of these variables on the waiting time is.

$$WT = AV \times M \times OT \quad (2)$$

Average Variability (AV): The average variability for calculating the waiting times consist out of two types of variability. The first one is variability in arrival times of orders. If orders arrive at a machine one hour apart consistently, there is not a lot of variability. However, when four orders come in the first hour and then none the next two hours, then you can say there is a lot of variability in arrival times. The second variability is the variability in job times. Similar to the first variability, if processing times are similar, there is not a lot of variability. But, when processing times differ all the time there is a lot of variability. Figure 3.5 clearly shows what the effect of variation is on the cycle time. The increase in cycle time will mostly be caused by an increase in waiting time.

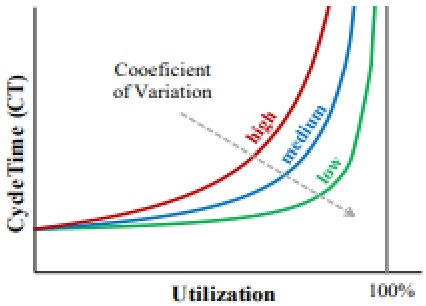

Figure 3.5: Impact of variation on cycle time

Magnifying factor utilization (M): The magnifying factor M can be calculated in the following way: $M = \frac{u}{1-u}$. The u in this formula is utilization. This means that as u approaches 1, the waiting times approach infinity. Utilization in QRM is ratio between time a machine/station is busy with any task compared to the total time production is running. QRM thinks that utilization should be lower than is usual in the traditional approach. Suri explains that utilization should be under 85% of capacity or even under 75% of capacity. On first sight a lower utilization seems to come with more cost, however QRM explains why this is not the case. Reserve utilization is needed to deal with dysfunctional variability. In reality there are many things that can cause production to take longer than planned, therefore having reserve capacity is a good thing.

The magnifying factor becomes 3 when the utilization is 75% ($\frac{0,75}{1-0,75} = 3$). When utilization increases to 90%, the magnifying factor becomes 9! This means that an increase of 15% in utilization leads to a waiting times that is three times as high. Disturbances in the production process also have a higher impact when the utilization is high. For example, when utilization increases from 90% to 95% due to unforeseen circumstances, the magnifying factor shoots up to 19 days. This is the reason why QRM aims to have utilization around 75-85%. In this way there is reserve capacity to deal with disturbances in the process, whilst also being relatively cost effective.

Order time (OT): The order time is the final factor in the formula for calculating the waiting time. Order time is the average time needed for an order, including changeover time.

3.2.3 How QRM can reduce waiting time

QRM explains how to decrease the waiting time, by zooming further in on the three aspects of the waiting time formula as given in section 4.1.2. After that some other ways to decrease waiting time as explained by QRM are given.

Reducing AV, the average variability

The average variability is calculated with the following formula:

$$AV = \left(\frac{AV^2 + JV^2}{2}\right) \quad (3)$$

Based on the formula we can conclude that one or both of the arrival variability (AV) and job variability (JV) need to reduce in order to reduce the average variability. Below is given how this can be done for both of these variabilities.

Reducing arrival variability (AV)

- Plan production to be more spread out over the week
- Is a machine earlier in the chain inconsistent with finishing jobs? For example if a machine works really fast, but also malfunctions regularly, this increases arrival variability and therefore also waiting time.

Reducing job variability (JV)

- Standardize procedures for changeover
- Standardize working procedures
- Plan series for productions such that job times are similar
- Reduce unplanned absence of employees
- Separate difficult orders from simple orders

Reducing M, the magnifying factor

To reduce the magnifying factor M, the utilization needs to decrease. Below, a few practical ideas to reduce the utilization are given.

- Investigate ways to reduce changeover time
- Invest in ways to reduce processing times
- Reduce rework and waste
- If a lot of machine failure → invest in preventive maintenance
- If a lot of absence of staff, try to reduce this
- If the above mentioned ideas do not lower the utilization, contemplate increasing the capacity with machines and/or people

Reducing OT, the time needed per order

- Reduce changeover time
- Reduce raw processing time
- Reduce rework and failure

Other ways to reduce waiting time

Find a good batch size. Batch sizes that are too big cause longer waiting times. Batch sizes that are too small, cause a lot of changeover time and therefore higher utilization.

3.3 Other theories on reducing waiting time

In this section, some other theories and articles are discussed on reducing waiting time. This section is mainly based on the book "Factory Physics" by Hopp & Spearman (2008). Other articles are used, however they provide very similar information as given in the book Factory Physics. "Factory physics is a systematic description of the underlying behavior of manufacturing systems" (Hopp & Spearman, 2008).

3.3.1 Relations for waiting time

The first relationship that will be discussed is Little's Law.

$$Little's\ law: WIP = TH \times CT \qquad (4)$$

WIP: WIP stands for work in process, which consists of inventory between the start and end points of a routing. In the case of this research, this will be the inventory of unfinished goods between phases of the production.

TH: TH stands for throughput, measured as the average output of a production process per unit of time. This can be split up in throughput for different production phases, or for the entire production process.

CT: CT stands for cycle time. Cycle time of a given routing is the average time from release of a job at the beginning of the routing (in this research at the laser) until it reaches an inventory point at the end of the routing.

Little's law is applicable to all production lines, not only those with zero variability. The following figure depicts an example for the relationship between throughput (TH), cycle time (CT) and work in process (WIP).

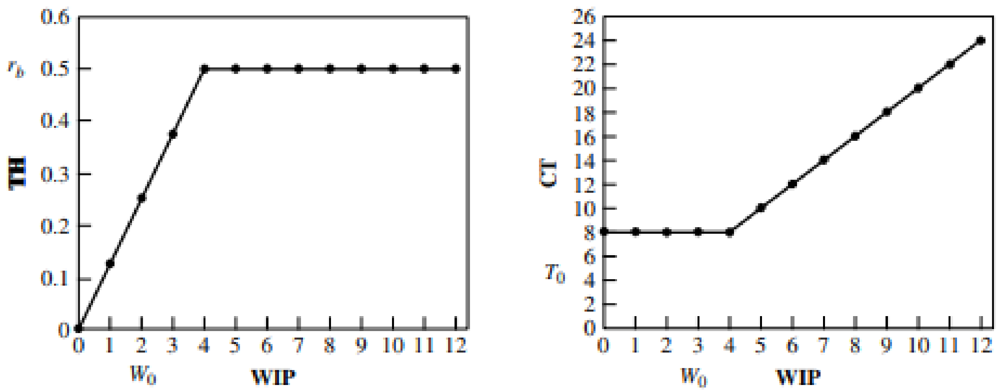

Figure 3.6: Relationship between WIP, TH and CT, from Hopp & Spearman (2008)

As can be seen in Figure 3.6, TH generally increase until a certain level of WIP. At this point the maximum throughput rate is reached, since there is always supply to the machine or line. After the WIP goes above this certain level, the TH cannot increase anymore as the machine or line simply cannot work that fast and the CT increases. The cycle time increases if the WIP goes above four in this case, since the product then has to wait before being processed at one of the workstation. In a balanced line consisting of stations with equal capacity, the critical WIP is equal to the number of machines. For unbalanced lines, as is the case at Senro, the critical WIP will be less than the number of machines. What can generally be concluded is that when WIP increases, throughput increases (good) and cycle time also increases (bad).

Variability

Variability exists in all production systems and can have an enormous impact on performance. The ability to measure, understand and manage variability is critical to effective manufacturing management (Hopp & Spearman, 2008). A definition on variability has already been given in Section 3.1, so this section will continue on how the variability can be reduced.

As described in Section 3.1 variability can have different causes (natural, failures, setups etc.). Since we know variability causes congestion, this can be reduced by addressing the causes of variability. Another, more subtle way of dealing with variability is by combining multiple sources of variability, also known as variability pooling.

When looking at process times of batches, the variability is lower than with individual parts, since is tenses to average out.

Utilization

We want high utilization to keep assets and unit costs down, but low utilization for good responsiveness. Utilization can be calculated by dividing the arrival rate at a station with the effective production rate.

To determine the effect of utilization on reducing waiting time. The formula on waiting time (CTq) that we will discuss is the Kingman's equation:

$$CTq = \left(\frac{c^2a + c^2e}{2}\right) \times \left(\frac{u}{1-u}\right) \times t_e \tag{5}$$

This equation is split up in a variability term (V), utilization term (U) and a time term (T), identical to the formula QRM uses for waiting time. It is not applicable to every process, but it offers some interesting insights. As discussed already variability (V) increases the waiting times, which the Kingsman equation also shows. In the utilization (U) part of the formula, it can be seen that the denominator is equal to 1-u. This means that as utilization approaches 1, waiting times go to infinity. The relationship between cycle time and utilization as given by Hop & Spearman (2008) can be seen in Figure 3.7.

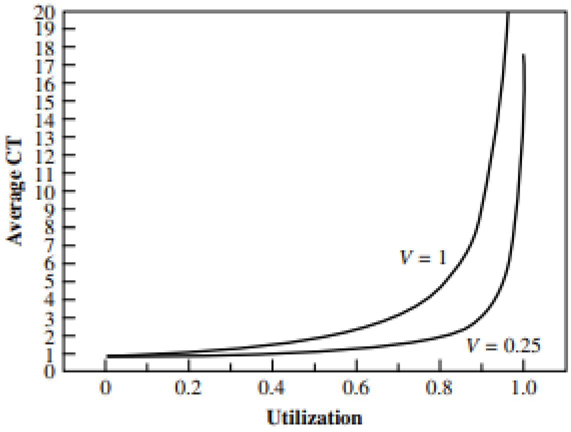

Figure 3.7: Relationship utilization, cycle time and variability (Hop & Spearman, 2008)

3.3.2 Reducing waiting times

In this sub-section we will discuss what the book ‘factory physics’ recommends to do with variability, utilization and processing times in order to reduce waiting times in production.

Variability

Variability is caused by different things like failures, setups as discussed before. Variability causes congestion in a manufacturing system, to reduce this variability, simply its causes need to be addressed. Some generic options Factory Physics provides are the following:

- *Setup reduction:* Smaller setup times lead to more frequent setups. More frequent variability decreases effective variability at the workstation.
- *Improved reliability:* Increasing mean time to failure or repair, reduces effective variability.
- *Enhanced quality:* Less rework and yield loss reduces effective variability.

Another way of dealing with congestion effects is by combining sources of variability also known as variability pooling. This can be done for example by increasing batch size, since less changeover time is needed then. Increasing the batch size however, has negative effects on the waiting times.

Utilization

In industry, cost accounting encourages high machine utilization. High utilization means higher return on investments, given that machine is utilized to generate revenue. Factory Physics promotes high utilization, provided that cycle times, quality and service is not degraded excessively. How high utilization can be for a certain line or station without significantly increasing the cycle time and WIP depends on the level of variability. A line with a high level of variability needs to have a lower level of utilization to compensate. Factory Physics provide the following generic options for reducing utilization:

- *Equipment changes/additions:* Replace machines with faster modules or add parallel capacity. This also comes with purchasing costs and effects on capacity and variability at a station.
- *Finite-capacity scheduling:* Regulate releases to production can reduce WIP. Systematic over releasing to the line is prevented in this way.
- *Setup reduction:* Reducing setup time increases effective capacity and thereby reduces utilization of a workstation.

- *Floating work:* Cross-trained workers can move to where capacity is required, increasing effective capacity and reducing utilization.

3.4 Conclusion

In this chapter the third knowledge question was answered. Theories and methods were found on how to reduce lead times in engineer-to-order companies, focusing on waiting times in production. To start of this chapter, we research what an engineer-to-order production approach entails and what the challenges are of this approach. We found that a lot of difficulties arise from the uncertain demand and specifications of products.

In both the QRM book and the Factory Physics book, it is mentioned that utilization, variability and time per order influence the waiting time. Utilization has a massive impact on waiting time, especially if it approaches 100%. QRM is different compared to traditional management, since the focus is on time instead of mostly cost-based. QRM advises utilization of 75-85% to deal with unforeseen delays.

The impact and definition of variability is also discussed in this chapter. We found that variability can be reduced by standardizing production processes, trying to prevent delays and by variability pooling. The impact of variability is larger with high utilization, and the effects of variability that happens upstream has more effect on delays than variability downstream.

To solve the research question, the theories in this literature review are combined. All theories discussed here have similar solutions for reducing waiting times by focusing on utilization levels, variability and processing times for a job. In Chapter 4, a Monte Carlo simulation model is built to test the impact of possible solutions on the waiting times that occur at Senro.

4. Model to test possible solutions

In this chapter, we build a model to test the impact of possible solutions to reduce waiting times between production phases. The model is needed to answer the third knowledge question. With this model some experiments will be done in Chapter 5, to see the effect of certain interventions in the model and to come up with good solutions . In this chapter first the choice for the type of model is motivated in Section 4.1. In Section 4.2 the conceptual model is given, which is needed to make a computer model. Further on, the validation of the model is given in Section 4.3 along with the final model.

4.1 Model choice

The model that we use for this research is a Monte Carlo Simulation. "Monte Carlo Simulations are used to model the probability of different outcomes in a process that cannot easily be predicted due to the intervention of random variables." (Kenton, 2020) This is a good choice for simulating different production phases at Senro, since the production process cannot easily be predicted due to variation in demand, employees available on a certain day amongst other things that cannot be predicted easily. The outcomes of the model, is a probability distribution from which we can see the most likely outcome. In this research, the model simulates 50000 independent days (explained in 4.2.3). This includes for example very unfavorable day where there are very few employees present, due to the (random) changes in input variables. By making a summary of all the simulated, a prediction can be made on the situation that is most likely to happen. The welding and the assembly department are simulated with the Monte Carlo simulation, since the data available for those department results in a more realistic outcome of the model and they were identified as focus of the research in Chapter 2. Whereas the data available on laser cutting and bending does not represent the reality good enough to validate using a Monte Carlo simulation.

4.2 Conceptual model

This section explains the conceptual model of the Monte Carlo Simulation. A conceptual model is a non-software specific description of a computer model, describing objectives, inputs, outputs, content, assumptions and simplifications of the model (Robinson, 2008). Therefore, in this section we discuss the following things: objective of simulation, input and output variables and limitations of the model in the form of assumptions and simplifications.

4.2.1 Objective of simulation

The objective simulation is to give a good representation of the current situation and as well to model the effect of certain interventions or solutions on important KPI's such as utilization levels and waiting times. This way we can see how the system is performing according to a computer simulation, compared to the actual system performance. The difference in results the interventions give can be used to support certain decisions. An example of an intervention is adding capacity in the form of an employee, what is the effect of the increased capacity on utilization levels and waiting times between production phases?

4.2.2 Input and output variables

In this section we give the input and output variables of the Monte Carlo simulation and explain the reason for using them in more detail as well as their relation. The input is all based on historical data, taken from the database at Senro. The input and output are categorized by welding and assembly in Table 4.1.

Table 4.1: Input and output variables of the model

Input variables	Output variables
Total work on a day	Total work on a day
Hours worked per person on a day	Employees present on a day
Variability arrival	Utilization level
Module processing times	Expected waiting time before phase
	Expected overtime days (%)
	Expected duration of overtime per person

Input variables

Most of the input variables are randomly drawn for each replication in the simulation. In Table 4.2 the distributions of the input variables can be seen. Six out of the eight input variables are generated based on an empirical distribution of the historical data. To determine the distributions for the input data, a probability plot is done and a goodness of fit test is done for the following datasets that are based on historical data: Total work done on a day, hours worked per person per day and processing times for modules. These tests can be found in Appendix C. Minitab is used to determine the fit of a probability distribution to the data sets of the aforementioned input variables. In Appendix C we explain in more detail how we test the fit to a certain distribution. The empirical distributions and how the input data is generated for a day in the simulation can be found in Appendix D.1.

Table 4.2: Distributions for all data sets

Data set \ department	Welding	Assembly
Total work done on a day (hours)	Empirical	Empirical
Hours worked per person per day	Empirical	Empirical
Arrival variability	Fixed number	Fixed number
Processing times for modules (hours)	Empirical	Empirical

Now that the distributions of the datasets for the input variables are determined, it is also necessary to explain the definition of each of these variables and show histograms of the data sets to roughly show the distributions that are used to generate input for the model. Only the histograms for welding are given to give a general idea of how the data set is distributed, since the histograms for assembly are similar. All input data apart from the arrival variability is drawn from an empirical distribution that was created by using historical data.

- *Total work on a day:* This input variable represents the total work that needs to be done on a simulated day. The histogram for total work on a day for welding can be seen in Figure 4.2. The average amount of work on a day is 43.93 for welding and 37.29 for assembly respectively, however as can be seen in the histogram this is very variable. This variability cannot be explained by seasonality, but rather that the demand is not consistent. And when delivery dates are close, a lot of work has to be done to finish on time.

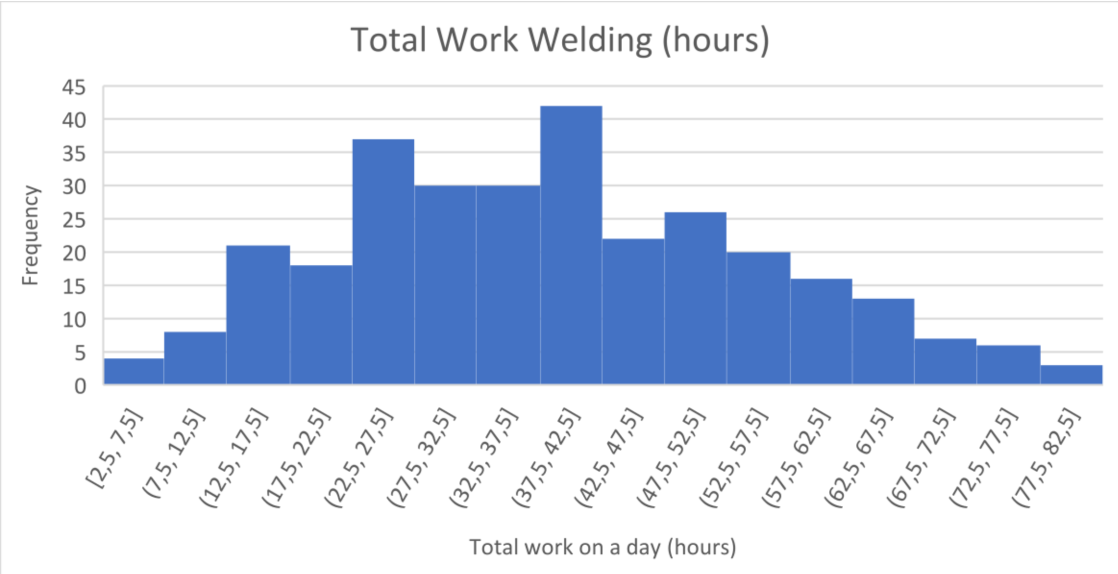

Figure 4.2: Histogram of total work for welding

- *Hours worked per person on a day:* This input variable is the average hours worked per person on a day. This was gotten by dividing the total work on day by the amount of employees that worked on that day. This input variable is needed to predict the amount of employees present on a day. The averages for hours worked per person on a day is 7.98 and 6.97 for welding and assembly respectively. In Figure 4.3 the histogram for hours worked per person for the welding department can be seen.

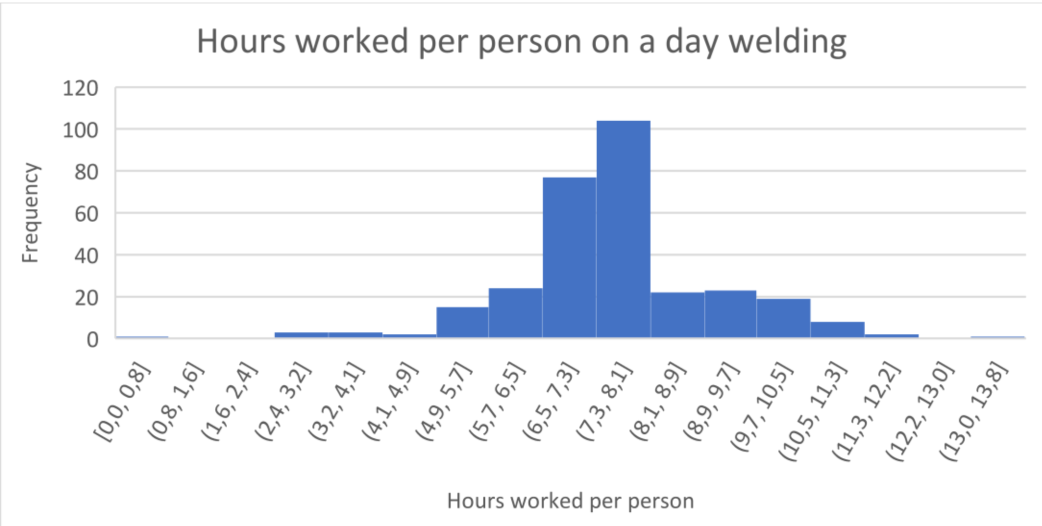

Figure 4.3: Histogram for hours worked on a day per person for welding

- *Variability:* The variabilities for arrival times and module processing times serve as the final input for the model. The variability is part of the formula that is needed to calculate the expected waiting times (see Equation 5). This formula also includes variability for processing times, however this is not used as an input, since that can be calculated after the Monte Carlo simulation is done. The arrival variability however, is not really possible to calculate with the model and therefore it is used as an input. The values are calculated by first looking at how many new modules are worked on per day. Then by dividing 1 by the amount of new modules on a day, we find the interarrival times. The variability of arrivals is then given by dividing the standard deviation of interarrival times by the average of interarrival times (Leanteam, appendix D). This gives the following two values for welding and assembly: 0.43 and 0.69.

- *Module processing times:* The distribution of the processing times for modules also serves as an input. This is needed to calculate the waiting time before a production phase as shown in Equation 5. These datasets are very variable in terms of hours needed, as can be seen in Figure 4.4 for welding. This is a logical consequence of the Engineer-to-order production approach, since each module is different.

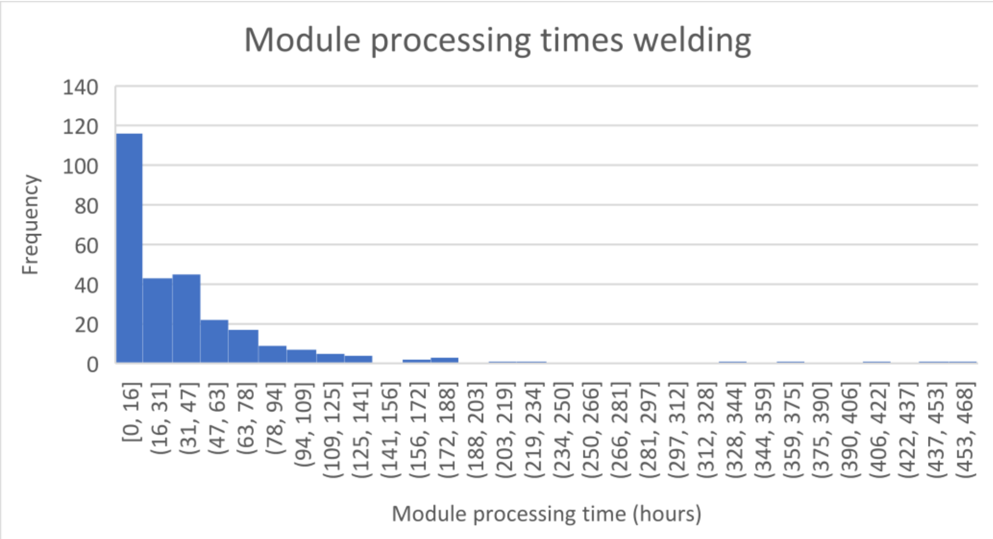

Figure 4.4: Module processing times for welding

Output variables

Now that we have explained the input data and have chosen a fitting distribution, it is time to explain what the output variables in the Monte Carlo simulation are and how they are calculated. One thing to note is that output variables may differ between different runs in the simulation. This is due to the big amount of randomness that is involved in the input variables of the simulation.

- *Total work on day*: Represents the total work that was done in a day in the simulation. The total work is calculated by taking the average of the total work that is done on each of the simulated days. The standard deviation is also calculated. This output variable is the average of the input variable of total work done on a day. This output variable is (almost) the same as the input for work on a day. The output variable is the average of total work on a day for all 50000 days.
- *Employees present on a day:* The number of employees present in production is used as output, since it can be used to determine utilization levels. The number of employees present on a day is calculated by taking the average of the expected employees on a simulated day. This column in the model is generated by dividing the total work generated on a day by the amount of work done per person on that day. How this is done, can be seen in Appendix D.1.
- *Utilization level:* Utilization level is the amount of work in time that is done compared to the total amount of time available. This heavily contributes to waiting time as shown in Chapter 3. It is calculated by taking the average of the utilization levels on all simulated days. On each day in the simulation, the utilization level is calculated by dividing the total work that needs

to be done on a day by the total time the employees can work on that day (8 hours). Equation 6 is used to calculate utilization.

$$Utilization = MAX\left(1, \frac{Total\ work}{8 * Employees\ present}\right) \tag{6}$$

- *Expected waiting time before phase:* This output variable is the most important of this research. It shows how long a module is expected to wait before it can be worked on at a production phase. This is similar to the waiting time between production phases. It is calculated using Equation 5 in Chapter 3.
- *Expected overtime days (%):* This output variable is the percentage of days overtime is expected to complete the work. This is an indicator to see how well the department can handle the amount of work it is given. It is calculated by calculating the amount of times the total work is higher than employees can handle in a 8 hour day. Since the simulation runs 50000 days, the final count is divided by 500. This gives the percentage of days where overtime is expected. Equation 7 shows the formula used for calculating expected overtime days.

$$Expected\ overtime\ days\ (\%) = \frac{(COUNT(Total\ work > (Employees\ present * 8))}{500} \tag{7}$$

- *Expected overtime duration per person:* This output variable depicts the expected duration of overtime when it happens. If this is a very high number, this is not good for employee morale. This variable is calculated by taking the average of overtime hours on days where overtime actually occurs and dividing it by the amount of employees that are present on that day. This way we get the amount of overtime hours needed per person when overtime occurs.

4.2.3 Warm-up length and run length

In this sub-section whether a warm-up is needed for the simulation and how many days we simulate in the model to get consistent results.

A warm-up period is needed, when the simulation needs to “fill” at the start. This applies to simulation that start empty and where outcomes of a day in the simulation is dependent on the state at the end of the previous day. This is not the case in this Monte Carlo simulation model. Days in the simulation are independent and based on historical data of days in the production process. That is why a warm-up period would not be improving the results are gotten and is not used for this model.

The amount of days that we run in the model is 50000 days. There are no rules of thumb or very straightforward formulas for determining the amount of replications (in this case days) to use for the simulation. However, the more days you simulate, the more accurate the results. To find the run length, some testing is done with the results with different run lengths. We keep on increasing the run length until the results for expected waiting time get consistent. The results can be seen in Figure 4.5.

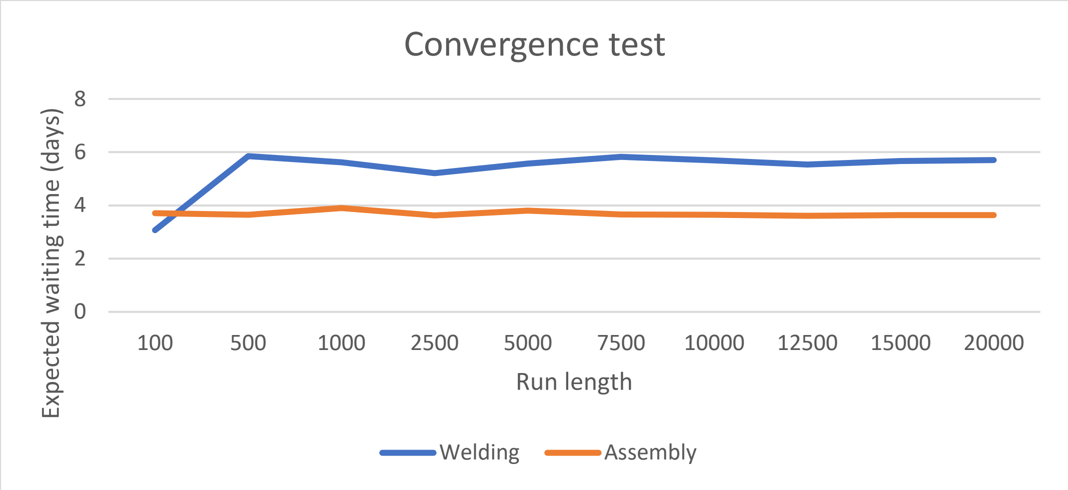

Figure 4.5: Testing run length needed based on convergence of waiting time

Figure 4.5 shows that the averages converge at a run length of around 15000. The rule of thumb for the number of replications is three to five replications (Law & McComas, 1990). Doing three replications for this Monte Carlo simulation takes more time than multiplying the run length by three. On top of that, results provided will be similar as the final output variables are averages. That is why one replication will be done, but with a longer run length. Based on the rule of thumb of Law & McComas (1990) the run length for the model is put at 50000 days.

4.2.4 Assumptions and limitations of the model

Before constructing the model, we need to be aware of the limitations the Monte Carlo simulation has and which assumptions are made. A good model is accurate and as simple to use and understand as possible. However, assumptions and simplifications have to be made in this research in order to construct the model. The assumptions of the Monte Carlo simulation are the following:

- The utilization levels cannot exceed 1. On a day where the amount of hours of work is equal to the amount of work the employees can handle or when overtime is needed the utilization is 1 in the model. This is done, because the total work done on a day can simply not be more than the employees can handle and weird KPI's will be produced if utilization goes above 1.
- The amount of employees present on a day is predicted based on the amount of work a person has done per day on average. This is done, since there is a direct link between amount of work done on a day and employees present in the historical data. For example: the average work done per person on modules is 7. Work that needs to be done is 40. The employees present on this simulated day is 40/7.
- Although we determine the amount of employees present on the amount of work they can do on a day, the utilization is calculated by the total time an employee has available on a day (8 hours in this research).
- When an employee is present, he is assumed to be working the full day in the model. In reality, employees sometimes leave due to sickness or do not work the full day.
- The Kingman equation (Equation 5) is assumed to be a good calculation for waiting times for the production phases at Senro. Suri (2010) also uses this equation to approximate waiting times.

The Monte Carlo simulation also comes with the following limitations:

- Data generated on a day in the simulation is independent. The day before the simulated day is not taken into account when generating total work on a day.
- The model cannot designate a certain period. The input for the model is an average of the last three years, since these averages of these three years gave similar data. You cannot set the simulation to run a busy or calm day specifically, but rather a random day based on the last three years.

4.3 The Monte Carlo simulation model

In this section the Monte Carlo simulation is shown. This section is split up in four parts. In Section 4.3.1 and Section 4.3.2 the model as shown to the user is explained. After that in Section 4.3.3 it is explained how input data is generated. Finally, Section 4.3.4 gives the validation and verification of the model.

4.3.1 Model home screen

The model home screen is the one of the two sheets that is shown to the user. In this sheet there are three buttons: run current situation, run custom scenario and clear tables as can be seen in Figure 4.6.

Figure 4.6: Home screen of Monte Carlo simulation model

When we press the “Run current situation” button, 50000 days get simulated based on historical data with no change in parameters. This results in output variables that closely represent the real situation at Senro. The table at the bottom of the home screen is left empty when this button is pressed.

When we press the “Run custom scenario” button, the user gets to put in values for the eight parameters that can be adjusted. This results in output variables that no longer represent the current situation, but a custom one. This button should be pressed when the user wants to do experiments.

The “Clear tables” button has the simple function of clearing the data in the tables. This is moreover also included in the code behind the other two buttons.

4.3.2 Histogram sheet

The second sheet that the user can access is the Histogram sheet. In this sheet, histograms for four different output variables are given for both departments: total work on a day, employees present, utilization levels and expected overtime hours per person. This way we can see the distribution and see the probability that the output variables is a certain value. After the user simulates either the current situation or makes a custom scenario, the histograms in this sheet are updated. In Appendix E, the Histogram sheet can be seen.

The histogram sheets is divided into two squares with both squares containing four histograms. The left square contains the histograms for the welding department. The right square contains the histograms for the assembly department.

If we zoom in on one of the histograms, it is clearer to see what information could be gotten from the histograms. In Figure 4.7, the histogram for the output variable total work on a day in welding department can be seen. From the graph the probability of a certain amount of work on a day can be seen. The total amount of simulated days is 50000. Therefore, if a certain amount of work appears 10000 times, the probability of having amount of work in that bracket is 20%. In the example of Figure 4.7, the probability that work on a day is between 20 and 23 hours is 6.4%.

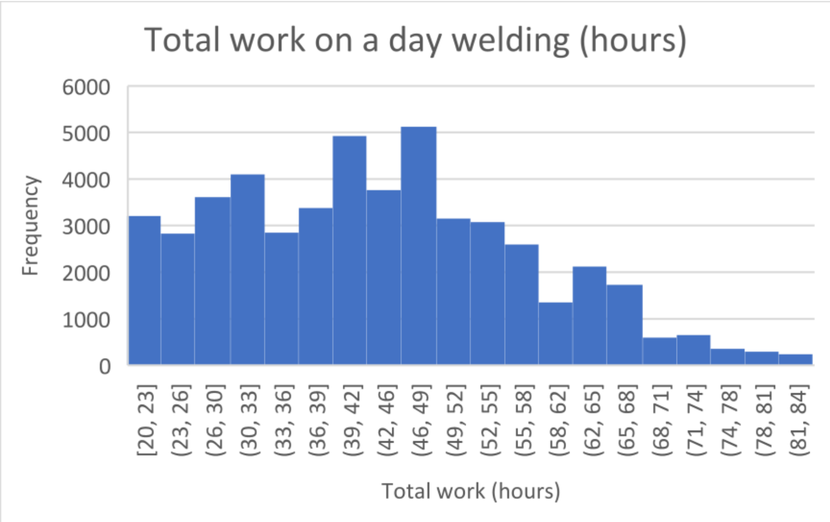

Figure 4.7: Histogram of output variable total work on a day welding

4.3.3 Input and calculations sheet

In this section it is explained how the data used as input for the model is generated. We explain how data is generated for one input variable. The input variable that is used for this explanation is hour worked per person on a day for welding. In Figure 4.8 it can be seen that a random number is generated, which is done for each individual variable, and also the hours worked per person on that particular day in the simulation: 10.75 hours.

Hours worked PP	
Welding	
0,976188414	10,75

Figure 4.8: Model input for hours worked per person at the welding department

The 10.75 hours are gotten from the empirical distribution that was made for the input variable as can be seen in Appendix D in Figure D.2. An example of what this table tells you is that around 25% of the time when a day is generated, the hours worked per person is 8 hours. This is the by far the most frequent hours worked per person on a day, which is very logical since a normal working day lasts 8 hours.

Input for total work on a day and processing times of modules are generated in a similar way. With these input variables the model can generate one day as shown in Figure 4.9. This is done 50000 times and with all these days averages and likelihoods of certain outcomes can be seen in the histogram sheet. The same thing is done for the assembly department. A histogram is a good graph to visualize the distribution of different outcomes. Histograms of output variables are given in a different sheet as explained in Section 4.3.2. The average output variables are shown in the model home screen.

Total work welding	Hours worked PP welding	Processing times welding	Employees present welding	Utilization welding	Overtime hours welding
47,5	8	7,5	6	0,99	0

Figure 4.9: One day in the simulation of welding department

The final part of generating the output for the Monte Carlo simulation that needs to be highlighted is about the experiments that can be done with the model. In the model there are some experiments the user can do. The user can run the simulation model with different scenario's. The changes the user can do is workload on a day, employees present on a day and variability levels for both the welding and the assembly department. The user input gets filled in at the place shown in Figure 4.10. In Figure 4.10 at the top you can see the current situation, below a random custom scenario. The way this changes the model is for example that when workload is upped by 8%, the total work on a day gets multiplied by 1.08 compared to the current situation.

Current scenario parameters	Extra employees	Workload change (%)	Variability change (%)	Moduletime change (%)
Welding	0	1	1	1
Assembly	0	1	1	1

Custom scenario parameters	Extra employees	Workload change (%)	Variability change (%)	Moduletime change (%)
Welding	1	1,08	0,98	0,99
Assembly	0	1,06	1,03	1,02

Figure 4.10: Difference in parameters current situation vs custom scenario

4.3.4 Model verification and validation

Model verification is about checking whether the model is designed correctly. This means that the model does not include mistakes and is similar to the conceptual version defined earlier on (Robinson, 2014). The model is verified by checking the results during the building of the simulation to see whether the outcomes were correctly calculated. Furthermore, some experiments were done with the model to see whether it behaves as expected.

In this section we also validate the model, meaning that we compare the results of the simulation with the historical data to see whether the model provides realistic results. We do this by simulating the current situation and comparing it with the historical data (expected results). The comparison between model and historical data for the welding department can be seen in Table 4.3.

Table 4.3: Model validation for welding department

Output welding	**Model averages welding**	**Expected averages welding**	**Difference**
Total work (hours)	43.02	43.93	0.91
Employees	5.73	5.52	0.21
Utilization	0,92	0.91	0,01
Expected waiting time (days)	5.77	???	**Explanation given below this table**
Expected overtime days (%)	26.70	24.15	2.55
Expected overtime hours per person	1.39	1.39	0

As can be seen it all is very sufficient for four out of the six output variables. The expected overtime days however, differs 2.55 percentage points with the historical data calculation. This difference can be explained by the fact that the relation the total work on a day and employees present on a day is not modelled exactly like it is in real-life. This difference however, is not that much and therefore we assume that the results of the model are sufficient enough for this research. The expected waiting time before the welding department is very hard to derive from the historical data, due to the fact that data is only tracked on module level and not part level. A part of a module can already be through welding whilst another part is still being bend. This makes it hard to calculate the expected waiting time. The real number is expected to much lower than the calculated number. This can be explained by the fact that Senro chooses to outsource work if the welding department can handle it. This results in a system that can have a high utilization without very high expected waiting times.

In Table 4.4 the comparison between the output results and historical data for the assembly department are given. The results from the model quite closely resemble the historical data. We can conclude that the results for the assembly department are sufficient for the purpose at hand.

Table 4.4: Model validation for assembly department

Output assembly	**Model averages assembly**	**Expected averages assembly**	**Difference**
Total work (hours)	37.46	37.29	0.17
Employees	5.52	5.36	0.16
Utilization	0.86	0.87	0.01
Expected waiting time (days)	3.69	3.50	0.19
Expected overtime days (%)	9.90	10.16	0.26
Expected overtime hours	1.12	1.11	0.01

4.4 Conclusion

In this chapter the model that is made test solutions to the main research question is explained. We started of this chapter with the choice for a Monte Carlo simulation due to the intervention of random variables at the production facility at Senro. We then went on to provide the conceptual model of the Monte Carlo simulation mode in Section 4.2. Section 4.3 provides the final Monte Carlo simulation model as shown to the user, as well as explaining how input data is generated.

5. Experiments with the model

In this Chapter, experiments are done with the Monte Carlo simulation model that was made in Chapter 4. In this Chapter, the third knowledge question is answered:

What are solutions for reducing the waiting times between the different production phases at Senro and what solution is the best?

This Chapter starts off by providing the results of the model when replicating the current situation. Section 5.2 shows the effect of changing one of the parameters on the output variables. Then in Section 5.3 possible solutions and their impacts are provided, followed by choosing the best solutions in Section 5.4.

5.1 Current situation

In Figure 5.1 the results of running the model in the current situation are shown. These are averages and calculations done based on 50000 days run length to give a better estimate of mean performance.

Table 5.1: Model results current situation

Welding department	**Average**	**Stdev**
Total work (hours)	43.01	13.96
Employees	5.73	2.14
Utilization	0.92	0.10
Expected waiting time (days)	5.69	
Expected overtime days (%)	26.88	
Expected overtime hours	1.39	0.88
Assembly department		
Total work (hours)	37.54	14.24
Employees	5.53	2.31
Utilization	0.86	0.11
Expected waiting time (days)	3.62	
Expected overtime days (%)	9.90	
Expected overtime hours	1.12	0.75

The results from the current situation represent reality quite well, there is only one value that is not easy to compare to the reality. This value is the expected waiting time at the welding department. The data is only tracked on module level, however work can already enter the welding phase on part level. Therefore it is not possible to check objectively whether this is a good value for waiting time. However, as discussed in Section 4.3.4 these output variables are good for the purpose at hand.

5.2 Single parameter interventions

In this section some experiments will be done with only one of the parameters to see what their influence is on the output variables. Based on the influence these parameters have on the output variables we can come up with solutions as well as provide some insights into performance of the production process.

Change in workload

When only changing this variable, the company can see how sustainable their current production process is when demand increases. The percentage of days where overtime is needed for welding is already at around 26 percent, so what happens when the workload is increased? The output variables that are interesting to look at when adjusting this parameter is utilization, expected waiting time, overtime days (%) and overtime hours. In Table 5.2, the output when workload is 1 percent higher than the current situation is shown. This immediately increases the amount of overtime days at welding from 26.88 to 38.03. This parameter can also be interpreted in a different way. If the employees adopt a more efficient way of working, this can also affect the daily workload in hours. If every job takes 2 percent less due to a different way of working, the workload is also 2 percent lower, which decreases waiting times and overtime days needed to complete the work.

Table 5.2: Output when workload is 1 percent higher compared to current situation

	Welding current situation	**Welding 1% work increase**	**Assembly current situation**	**Assembly 1% work increase**
Total work	43.01	43.54	37.54	37.75
Employees	5.73	5.73	5.53	5.51
Utilization	0.92	0.93	0.86	0.86
Expected waiting time (days)	5.69	6.37	3.62	3.90
Expected overtime days (%)	26.88	38.03	9.90	13.68
Expected overtime hours	1.39	4.25	1.12	3.01

Other experiments where only the workload is changed can be found in Appendix D.1. What can be derived from the table is that the expected waiting time and expected percentage of overtime days increase rapidly with a growing amount of workload on a day. This is to be expected, since increasing the workload has a direct impact on the utilization. Utilization in turn has the biggest impact on waiting time as found out in the literature review in Chapter 3. In Figure 5.1 a graph can be seen how the expected waiting time changes for both departments with different workloads.

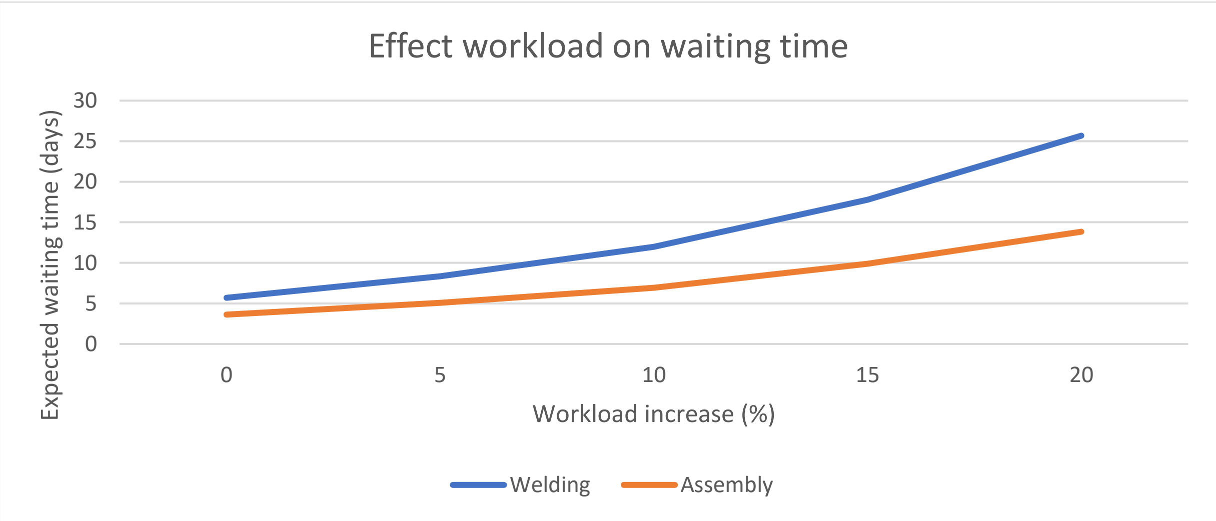

Figure 5.1: Effect workload increase on expected waiting time

Change in employees

Not only can effective capacity be increased by working more efficiently, it can also be added in terms of employees in this case. In Table 5.3 the output of adding 1 employee to both departments can be seen. Adding one employee is a lot of extra capacity, which can directly be seen in the new utilization, waiting time and overtime days. Adding 1 employee makes the waiting time for the welding department 3 times as low. The overtime days occur 4 times less at welding when one employee is added. It does give a much lower utilization rate of 0.8 meaning that 20 percent of the day employees are not working on a module. Overall, adding employees enhances performances, but the employee is out of work more frequently. One remarkable result is that the overtime hours increase at both departments. So days where overtime is needed decreases, however when it occurs the employees have to work for a longer time.

Table 5.3: Output when adding 1 employee in both departments

	Welding current situation	Welding extra employee	Assembly current situation	Assembly extra employee
Total work	43.01	43.07	37.54	37.41
Employees	5.73	6.73	5.53	6.53
Utilization	0.92	0.80	0.86	0.71
Expected waiting time (days)	5.69	1.90	3.62	1.29
Expected overtime days (%)	26.88	6.83	9.90	1.23
Expected overtime hours	1.39	3.40	1.12	2.61

In Appendix D.1 experiments are done with adding or removing employees. The results these experiments have on the expected waiting time can be seen in Figure 5.2.

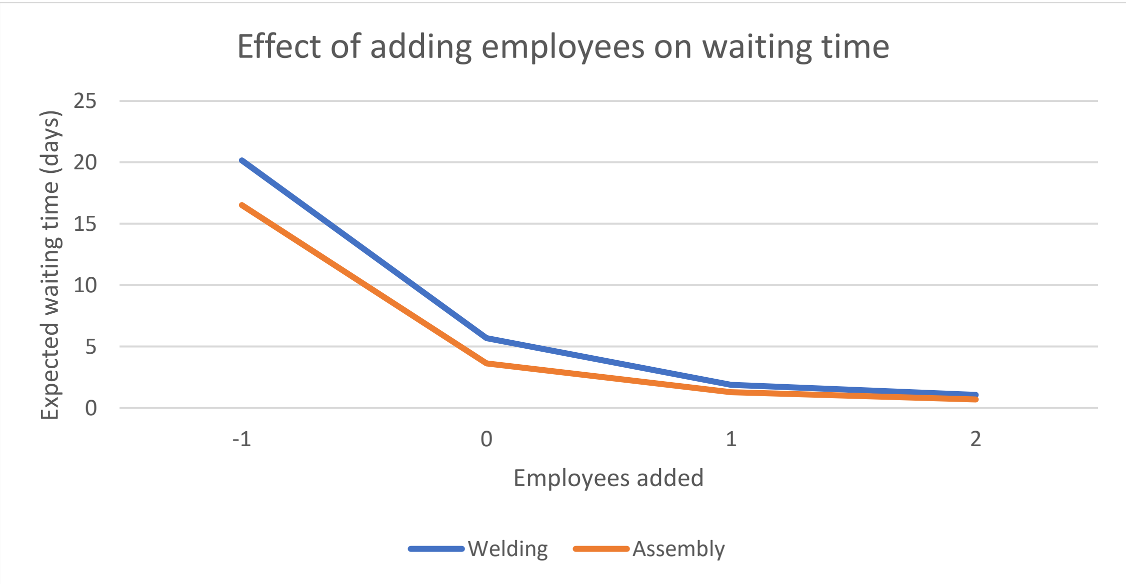

Figure 5.2: Effect of adding employees on waiting time

Change in variability

The effect of changing the variability on waiting time is up next. With variability, the variability in arrivals of modules and variability in processing times is included. This parameter only influences one of the output variables: The expected waiting time. In Figure 5.3 the effect of five different values for variability are given. The effects of changing the variability is not as big as the effect of changing capacity or work load. However, improving on this still provides results that are significant enough that it is worth looking at.

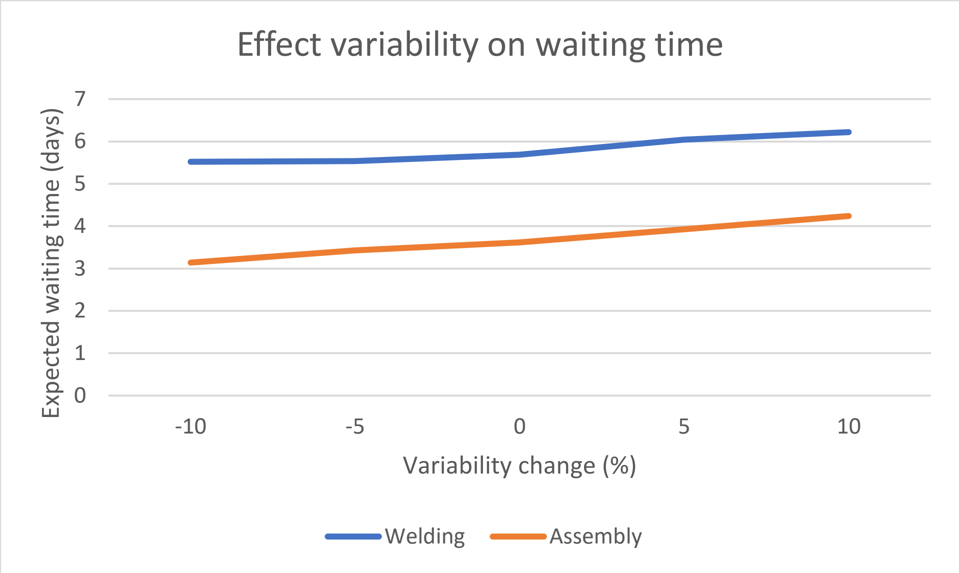

Figure 5.3: Effect of variability on waiting time

Change in processing time per module

The last parameter that can be changed is the total processing time per module. In reality this can only change when staff works faster. Figure 5.4 shows the influence of processing time per module on waiting time. Similar to variability, the processing time per module only influences the expected waiting time for a module. The influence of this parameter is also not as significant as the first two parameters discussed in this section.

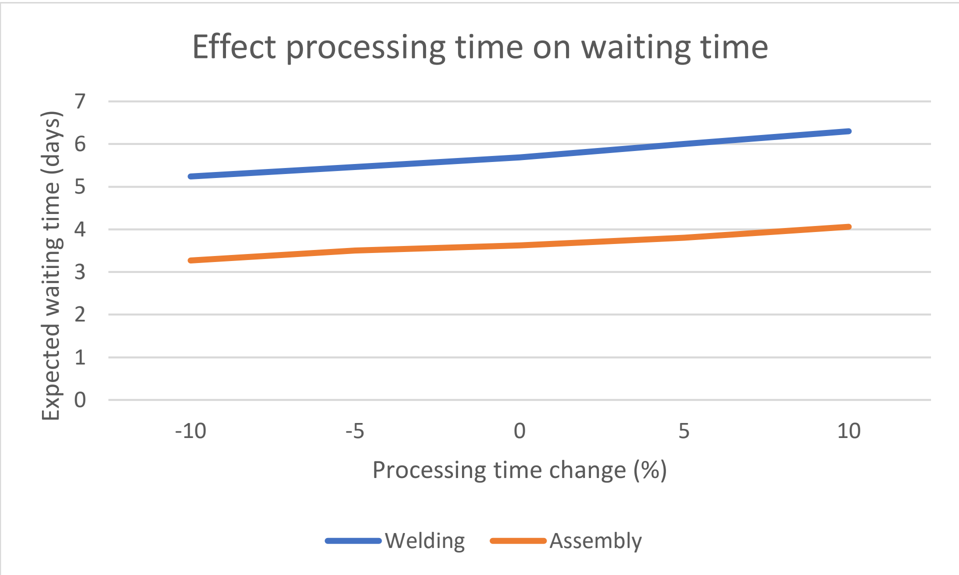

Figure 5.4: Effect processing time on waiting time

5.3 Solution approach for reducing waiting time between production phases

In this section we go to a solution approach for Senro to reduce the waiting time of modules between production phases. The solutions tested in this section are chosen mostly based on the literature review in Chapter 3 and the parameter interventions in Section 5.2. Section 5.3.1 is about reducing variability, Section 5.3.2 about reducing utilization levels. For each of the solutions we discuss the trade-offs that solution comes with.

5.3.1 Reducing variability

In this sub-section, it will be explained what Senro can do to reduce waiting times by taking a look a variability in the production process. The effects of reducing the types of variabilities discussed in this section are tested in the Monte Carlo simulation to determine whether these are worthwhile solutions.

Variability in workload

Currently the workload is on a day has a lot of variation in it. As seen before in Table 5.1 the standard deviation for work on a day in welding is almost 14 hours on an average of around 43 hours. The standard deviation for work on a day in assembly is more than 14 hours on an average of around 37 hours. In Figure 5.5 the fluctuations of total work can be seen. The red dots in the graphs are the moving averages, which show that the workload is not evenly spread throughout the years. This is also somewhat expected, since demand is very uncertain at Senro. In this sub-section, we will test what happens to the expected waiting times when this variability in work load on a day is reduced. We expect the arrival variability to reduce when the work load is spread out more evenly, which impacts the expected waiting time.

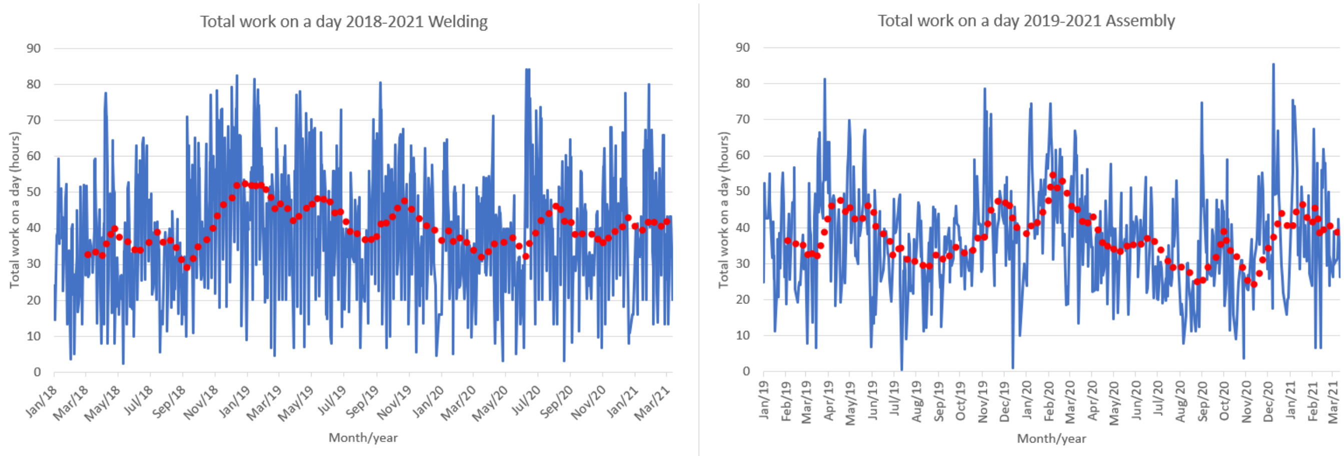

Figure 5.5: Fluctuations in total work on a day for welding and assembly

The way to test this solution is to make new empirical distributions for the work load on a day for both departments, where we allow less variability. In Table 5.5, the difference in expected waiting time is shown, when standard deviation is lower. For both department it can be seen that when the standard deviation of total work load is decreased, it also decreases the expected waiting time. The effect of reducing the variation in demand is not very big. From Table 5.5 we can derive that when standard deviation for total work at assembly decreases from 14.22 to 7.60 the expected waiting time only decreases 0.39 days. Taking into account that decreasing this deviation in total work is hard for a company with an Engineer-to-order production approach, we can conclude that focusing on reducing variation in work load should not be priority number one. It is however, good to try to spread out workload, since this reduces the amount of very busy periods, as well as reducing the expected waiting time between production phases.

Table 5.5: Effect of deviation of total work on expected waiting time

	Total work	Stdev	Expected waiting time (days)
Welding			
Current situation	43.01	13.91	5.69
Lower variation in workload	43.04	7.50	4.81
Assembly			
Current situation	37.54	14.22	3.62
Lower variation in workload	37.67	7.60	3.23

By halving the standard deviation for total work on a day for both departments, a total reduction of waiting time of 1.27 days is gotten. This is a reduction of the total production lead time of 4.33%. Now that we can see the results of reducing the variability in workload, it is time to discuss the tradeoffs. The advantage of this solution is that waiting times decrease when variability in workload is decreased, however variance needs to be reduced significantly to get good results.

Variability in employees

The next variability we take a look at is the variation in employees that are present in production. Will the expected waiting times decrease when the amount of employees present in production is more stable? To test this, again a new empirical distribution for employees is made in which the variation is less. This way we can test whether a reduction in standard deviation has a positive influence on expected waiting time. In the new empirical distribution we allow less variance for hours worked per person on a day, which is used to calculate amount of employees present on a day as explained in Chapter 4. By doing this, we cannot decide on a certain amount of reduction in variance, however we can calculate with the model if a reduction in variance positively impacts the output variables.

The effect of less variability in employees can be seen in Table 5.6. What is remarkable is that at welding, the expected waiting time slightly increases, whereas the expected waiting time at assembly slightly decreases. This can be a result of the change in the empirical distribution that turned out to be unfavorable for the welding department. Therefore we assume that the variability in employees does not affect expected waiting time significantly enough. Reducing the variation does have a major influence on the expected overtime days and the overtime hours needed (see Table 5.6). Therefore, we can conclude that reducing variability in employees is something that Senro should be trying to do. Averages for total work, employees and utilization are left out of the table, since they do not change.

This solution comes with some advantages, however also with a big disadvantage. The advantages of this solution can mainly be seen in Table 5.6. Reducing the variance in employees decreases the percentage of overtime days and the number of expected overtime hours. This results in more satisfied employees. The biggest disadvantage of this solution comes from the fact that this solution needs future research on how to implement this. Variance in employees is dependent on a lot of factors that are not controllable. Therefore, reducing variance in employees is likely very hard to accomplish, even when future research is done.

Table 5.6: Effect of reducing variance in employees present

Welding	**Current situation**	**Lower variance in employees**
Employees standard deviation	2.15	1.93
Expected waiting time (days)	5.69	5.75
Expected overtime days (%)	26.88	19.67
Expected overtime hours	1.39	0.86
Assembly		
Employees standard deviation	2.31	2.13
Expected waiting time (days)	3.62	3.46
Expected overtime days (%)	9.90	2.22
Expected overtime hours	1.12	0.18

5.3.2 Reducing utilization levels

In this sub-section possible solutions are given on how Senro can reduce the utilization levels of the welding and assembly department. The impact of these solutions is tested in the model. According to the Quick-Response manufacturing strategy discussed in Chapter 3, the utilization level at these departments should not exceed 85%. In the current situation the welding and assembly department have higher utilization: 92 and 86% respectively.

Increasing effective capacity

Utilization levels can be decreased by adding capacity, but another way to do this is by increasing the effective capacity. By working more efficient, the effective capacity increases and the total work on a day in hours becomes less. The reason for this is when increasing effective capacity, the same amount of work can be done in less time. At Senro there is room for an improvement in effective capacity. Especially when storing items temporary, there is some inefficiency. Employees sometimes need items in the back of the storage and in order to get there they have to move stuff. This does not add value and therefore decreases effective capacity. In this thesis, it is not researched how the effective capacity can be improved, but rather we show what the results are if the effective capacity increases. That is why one of the recommendations in Chapter 7 is to do future research in to how effective capacity can be increased.

To test the effect of increasing the effective capacity, experiments are done where the workload is decreased on a day. When effective capacity increases 1 percent, the workload decreases by 1 percent. Then based on the output variables, we can determine the impact of this solution. For this solutions a few situations for increase in effective capacity are tested: 1, 3 and 5 percent. An increase of 1 percent is a target that is very feasible to reach, whereas 5 percent is a bit less likely. The results can be seen in Table 5.7. What can be derived from the table is that the effect of increasing effective capacity is bigger at the start, since the difference between 1 and 3 percent is bigger than the difference between 3 and 5 percent.

Table 5.7: Results when increasing effective capacity.

Effective capacity increase →	0% (Current situation)	1%	3%	5%
Welding				
Total workload (hours)	43.12	42.63	41.74	40.90
Employees	5.75	5.73	5.73	5.75
Utilization	0.92	0.91	0.90	0.89
Expected waiting time (days)	5.70	5.22	4.41	3.79
Expected overtime days (%)	26.75	23.67	21.40	20.54
Expected overtime hours	1.40	1.32	1.27	1.11
Assembly				
Total work (hours)	37.38	37.06	36.36	35.55
Employees	5.52	5.52	5.53	5.52
Utilization	0.86	0.85	0.83	0.82
Expected waiting time (days)	3.67	3.43	3.00	2.67
Expected overtime days (%)	9.97	7.96	7.10	6.23
Expected overtime hours	1.11	1.04	0.99	0.92

From Table 5.7, we can conclude that increasing the effective capacity impacts the expected waiting time significantly in a positive way. Increasing effective capacity moreover improved all other output variables positively where possible. The disadvantage of increasing effective capacity is that future research is needed to identify where work can be done more efficient at the welding and assembly department. This is definitely worth to research further based on these results. To visualize the decrease in expected waiting time as a result of increasing effective capacity, a graph can be seen in Figure 5.5. With future research, effective capacity can most likely be improved at Senro. An increase of 5% in effective capacity is assumed to be possible at Senro. When effective capacity increases by 5%, the expected waiting time decreases by 2.90 working days. This is a reduction of the total production lead time of 9.9%.

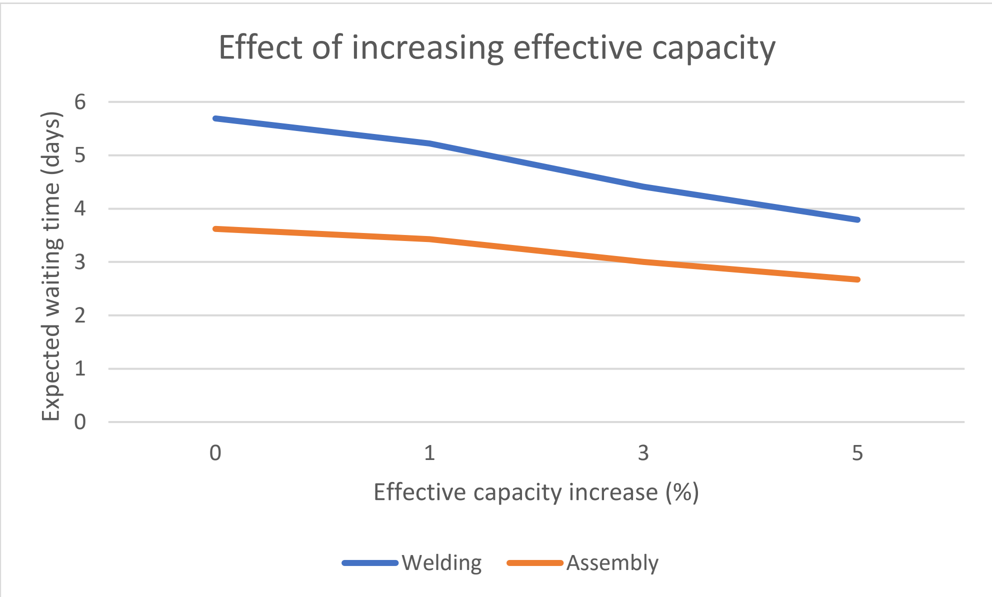

Figure 5.5: Effects of increasing effective capacity on waiting time

Adding capacity

When the effective capacity cannot be increased (anymore) like described above, capacity can also be added to the two departments in terms of employees. In Section 5.2 the effect of adding 1 employee to both departments was already given in Table 5.2. There we can see that the utilization levels already drop to 80 percent for welding and 71 percent for assembly when 1 employee is added in both departments. This is a bit too much, and that is the reason for taking a “flexible worker”. This is a worker that can work in both welding and assembly. Currently there is already at least one flexible worker. The flexible worker can be used in both departments, however should be used more in welding since that department is more highly loaded. The best ratio between working in the departments is 70/30, as this gives the lowest combined expected waiting time. The results of adding an extra employee that works for 70 percent at welding and 30 percent at assembly can be seen in Table 5.8.

Table 5.8: Effect of extra flexible worker working 70% in welding and 30% in assembly

	Welding current	**Welding (70% extra employee)**	**Assembly current**	**Assembly (30% extra employee)**
Total work (hours)	43.01	43.05	37.54	37.47
Employees	5.73	6.44	5.53	5.83
Utilization	0.92	0.84	0.86	0.81
Expected waiting time (days)	5.69	2.45	3.62	2.43
Expected overtime days (%)	26.88	11.93	9.90	5.32
Expected overtime hours	1.39	0.70	1.12	0.80

The utilization levels for both departments now are below the 85 percent that Quick-response manufacturing recommends. This results in lower waiting times, but also improves the expected overtime days and expected overtime hours compared to the current situation at the company. This solution is relatively easy to implement, however comes with the highest direct cost. Also there is a restriction on space. For example, at the welding department there is currently only room for seven welders, so space restriction is also something to keep into account. This solution reduces the expected waiting time by 4.43 working days. This reduces the total production lead time by 15.1%.

Outsourcing work

Another way to reduce the utilization levels in the production, is to outsource work to external parties. This is already happening a little bit, however the utilization levels are still high especially at the welding department. Outsourcing work means that there is less total work that needs to be done on a day, which lowers the utilization of the internal capacity. In Figure 5.6, the effect of outsourcing work for the welding and assembly department on the waiting time is depicted. Based on this graph we can determine how much work ideally needs to be outsourced to reduce waiting times, whilst still being cost-effective. In Figure 5.6, we can see that the waiting time decreases the fastest at a lower percentage of work that is outsourced and that the effect on the welding department is significantly larger than on the assembly department in absolute values.

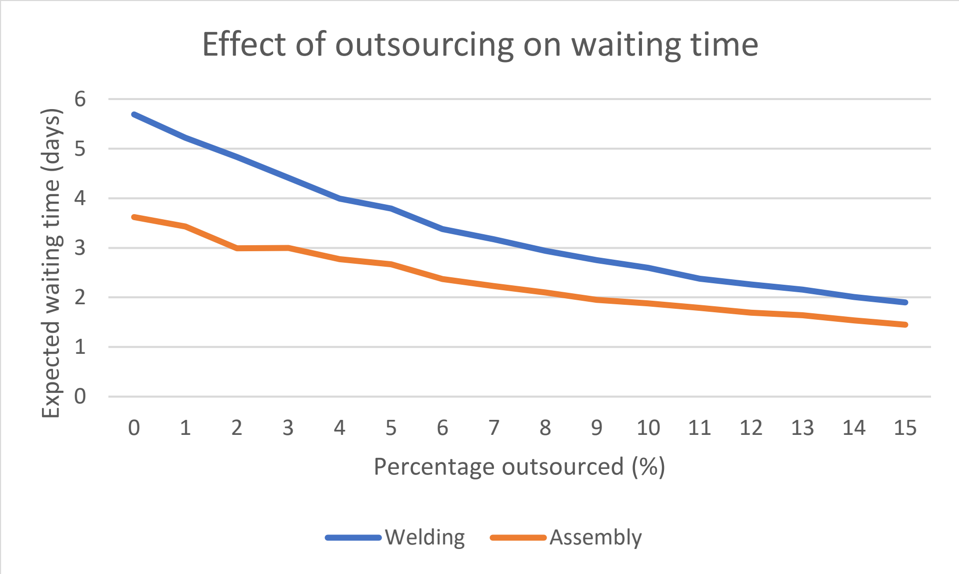

Figure 5.6: The effect of outsourcing work on the waiting time.

Based on Figure 5.6, the amount of work that is advised to outsource per department is the following: 10% for the welding department and 5% for assembly department. These values are chosen, since a good reduction in waiting time is gained and outsourcing even more is less interesting when waiting times are lower. The reduction of waiting time that is gained when outsourcing 10% of welding and 5% of assembly is 4.23 working days. This is a reduction of 14.4% of the total production lead time. In Table 5.9 the effect of outsourcing 10% more welding work and 5% of assembly work on the output variables can be seen. Outsourcing reduces the waiting times, expected overtime days and expected overtime hours. The disadvantage is that outsourcing is more expensive than doing the work in-house.

Table 5.9: Effect of outsourcing 10% of welding and 5% of assembly

	Welding current situation	**Welding 10% outsourced**	**Assembly current situation**	**Assembly 5% outsourced**
Total work (hours)	43.01	38.80	37.54	35.53
Employees	5.73	5.73	5.53	5.53
Utilization	0.92	0.85	0.86	0.82
Expected waiting time (days)	5.69	2.74	3.62	2.68
Expected overtime days (%)	26.88	16.30	9.90	6.31
Expected overtime hours	1.39	0.84	1.12	0.93

5.4 Ranking the solutions

In Section 5.3 five different solution approaches were given to reduce the expected waiting times before the welding and assembly departments. All these solutions have their own benefits. In this section we determine the best solution by looking at the ease of implementation, the impact it will have and the costs to implement the solution. The scores assigned for these criteria are based on the results, advantages and disadvantages identified for the solutions in Section 5.3. A weighted decision matrix is made for this and based on the results of this a ranking can be made for the order in which these solutions have to be implemented. In cooperation with the operations manager (and supervisor) criteria and weights of these criteria have been determined. The chosen criteria are the following: feasibility, impact and cost. The weights are between 1 and 5. A higher value shows that that option is more favourable for that criterion.

Table 5.9: Weighted decision matrix for solution approaches

Aspect	**Feasibility**	**Impact**	**Cost**	**Total**	**Ranking**
Weights:	5	3	3		
Reduce variability in workload	3	2	3	31	3
Reduce variability in employees	1	3	4	26	4
Increasing effective capacity	3	3	4	36	2
Adding capacity	4	5	1	38	1
Outsourcing work	4	4	2	38	1

Based on the matrix in Table 5.9, the best option to start with is adding capacity in the form of employees or free up capacity by outsourcing work to external parties. These solutions come with a cost, since salary needs to be paid for the employee and outsourcing is more expensive than doing it yourself. However, doing this ensures the maximum of 85 percent utilization that QRM advises and brings more peace to the work floor. Increasing effective capacity came up as the second best solution. This solution has less impact on the output variables and requires some extra research, however implementing this is cheaper than the two solutions that scored the best. The "worst" solutions are reducing variability in employees and reducing variability in workload. The reason these solutions scored the worst, comes mostly from the effort it takes to implement them. For both reducing variability, extensive (future) research has to be done to identify improvement points. Reducing variability in workload can be very hard due to deadlines and wishes of customers regarding deadlines.

5.5 Conclusion

In this Chapter, experiments were done with the Monte Carlo simulation model in Chapter 4. First, single parameter interventions were done with the model from which we can conclude that a change in workload and a change in number of present employees have the most effect on the expected waiting time due to their direct relation with the utilization levels. Furthermore we came up with a few solutions and tested their impact in the model. The solutions were then put in a weighted decision matrix to determine the best solution, which ended up being an addition to the capacity in terms of employees or outsourcing some work from the welding and assembly departments.

6. How to implement the solution(s)

In this chapter, the practical implementation of the proposed solutions are described as this Chapter aims to answer the fourth research question:

How can the solutions be implemented?

In this Chapter we once again go over the reason why implementation might be needed at the company in Section 6.1. In Section 6.2 the steps that need to be taken for implementation for the solutions is given.

6.1 Reason for implementation

To start off this chapter, we once again discuss the reason as to why these solutions might be needed at the company. In Chapter 1 a problem cluster was made and the action problem is the following:

"Too low on-time delivery performance"

One of the core problems that contribute to this action problem is the fact that there was no insight in waiting times between production phases and how to reduce them. That is why this research focuses on waiting times as reducing them means an increase in the on-time delivery performance. Lowering waiting times in production also mean lowering lead times, which gives a better position for Senro in negotiations with customers due to an increase in flexibility and responsibility. At the start of the research a 28.5% reduction of production lead time was set as a target and the way to accomplish that in this research is by reducing the waiting time between production phases.

6.2 Implementation per solution

In this section we briefly describe for the two best solutions provided in Chapter 5 how they can be implemented. The reason we do this only for the two best solutions, is because they are most likely to be considered as best solution for the company and do not require further research. A good way of making an implementation plan is by dividing it into two sides: technical and social (Heerkens & van Winden, 2017). The technical side describes the activities that need to be performed to implement a solution. The social side describes the roles of individuals and how to get them on-board with the change.

Adding capacity

Technical side: This solution is quite simple to implement on the technical side. In Chapter 5, we found that capacity should be added with 1 flexible employee that works for 70 percent in welding and 30 percent of the time in assembly. This can also be done in another form, for example by adding 1 person to welding and then have one person in welding work for 70 percent of the time in welding and 30 percent of the time in assembly.

Social side: The hardest part of this solution is to get the individuals that are involved with this change on-board. This is solution is a bit unorthodox compared to traditional beliefs in production as the focus is here on time instead of cost. With this solution, both the welding and assembly department will have utilization levels below the 85 percent that Quick-Response manufacturing advises.

For management, the reason to implement this has been stated before. When utilization decreases, the expected waiting times and other variables like overtime decrease as well as seen in Table 5.8. The expected waiting time of both departments combined decrease by 4.43 working days, which is a reduction of 15.1% of the total production lead time. Furthermore, 85% utilization does not mean that employees should be doing nothing in the time they do not have work. With this reserve time, employees can think about improvement strategies for their department and deal with variability in production better. It is hard to determine objectively how beneficial this solution is in money, since there is no direct relation between production lead time and money. However, Suri claims that cost will go down when the lead time is reduced with the following formula based on earlier cases of QRM (Leanteam, 2017):

$$CR = (LR)^{\frac{1}{6}} \tag{8}$$

Where CR stands for cost ratio with the current situation and LR for lead time ratio with current situation. The current lead time is 29.36 (working) days. In the new situation we will have 4.43 days less, making it 24.93 days. The value for LR therefore becomes 0.85. The CR value then becomes 0.973. This means a reduction of total cost 2.7%. This formula is taken from the QRM book ' It's about time' and is based on completed QRM-project in the past to give an estimation of the cost reduction.

Employees on the work floor might also be hard to convince of the benefits of this solution. These employees should be convinced of the benefits this solution will have after managers believe in it. For employees these solution means a more calm and controlled working environment especially due to a decrease in periods where workload is (too) high. There is also more time available to think of improving the working methods used.

Outsourcing work

Technical side: For the implementation of this solution it is first of all important to look at what work needs to be outsourced. It is recommended that work with less priority gets outsourced, since it most likely takes longer for the outsourced work to be back than when this work is done in-house. Also a company needs to be found that can consistently take on work from Senro. The amount of work that is recommended to outsource is 10% more welding and 5% from the assembly department. One thing to note: if the company chooses to add capacity, then outsourcing work should not be done and the other way around.

Social side: Similar to the adding capacity solution, this solution is also focused on reducing the utilization levels to become lower than 85%. Therefore, this solution also builds on the beliefs of QRM and not the traditional beliefs where focus is mainly on costs.

For management, there are a few reasons this solution should be considered. Outsourcing 10% of welding work and 5% of assembly reduced the combined expected waiting time by a total of 4.23 working days. This is a reduction of 14.4% of the total production lead times. The output variables for expected overtime days and overtime hours also reduced as seen in Table 5.9. Similar to the adding capacity solution it is hard to determine what the effect of this solution is in terms of cost. Of course, outsourcing is more expensive than doing it in-house, but a lower lead time can reduce costs. To estimate the cost benefits of this solution, we use Equation 8 again. LR in this case is 0.856. This makes CR 0.974. The expected cost reduction is therefore 2.6%.

7. Conclusion and recommendations

In this final chapter the conclusion, discussion and recommendations of the performed research are provided. Section 7.1 covers the final conclusion of the research and answer to the main research question. Furthermore, in Section 7.2 a discussion is provided. Based on the conclusion and the discussion of the research, recommendations are given to Senro in Section 7.3. Section 7.4 provides the practical and theoretical contribution of the research before ending with future research possibilities in Section 7.5.

7.1 Conclusion

This section answers the main research question of this research. The answer to the main research question is based on the answers of the four knowledge questions answered in Chapter 2 until Chapter 6.

At the start of the research, interviews were done with important stakeholders. Based on these interviews, the problem cluster in Figure 1.2 was constructed. The core problem that we found is that that there was no good insight into waiting times between production phases and modules were waiting quite long. That is why the focus of this research is on identifying the waiting times and come up with ways to reduce them. This resulted in the following main research question:

What are the causes of modules waiting between production phases at Senro and how can they be reduced?

With the current situation analysis, which was mostly done with data analysis and interviews, we identified the flow of modules in terms of time and routing as well as some causes of waiting times. The total production lead time is 29.36 working days. Furthermore, we determined on *module level* how long a module was at certain production as well as when it entered and exited that phase on average. This resulted in the timeline in Figure 7.1.

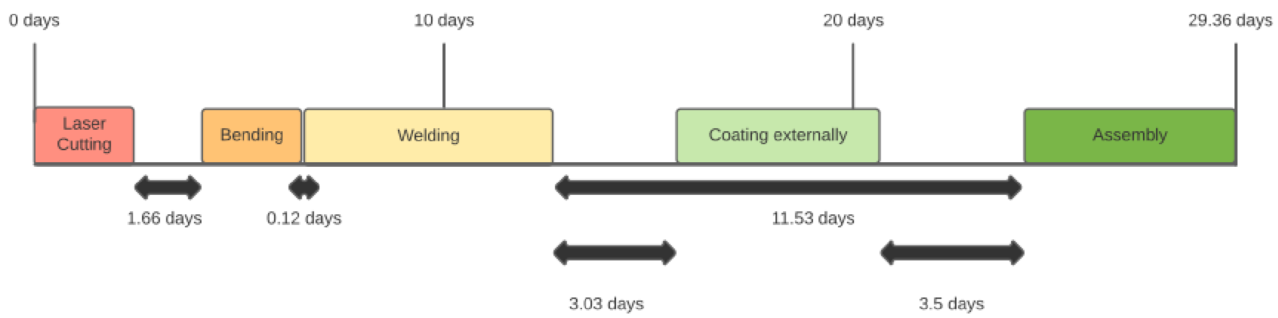

Figure 7.1: Average timeline of a module

Then the welding and assembly department are chosen as bottlenecks. The main reason for this is that the waiting times are the highest before these departments. Another reason for not including the laser cutting and bending phase is that the data available on these phases is not good or cannot be used to provide valuable insights.

From the literature review, in which we looked at the QRM theory and the causes of waiting times, some factors that contribute to waiting times are identified. Utilization level has the most impact on waiting times, followed by the average variability and processing time for a module. Reducing these factors, leads to a reduction in waiting times as well.

In Chapter 4, a Monte Carlo simulation model was build. With this model we can simulate the performance of the welding and assembly department in the current situation in terms of expected waiting times, but also some other interesting variables. With the model, a custom scenario can be simulated to experiment with different scenario's. Based on the experiments, we know what has an impact on the performance of these two departments. Therefore, by first doing the experiments and taking the literature review into account we came up with relevant solutions. Five solution approaches were tested in the model of which two are based on reducing variability and three on lowering the utilization levels at the departments:

- Reducing variability in workload
- Reducing variability in employees
- Increasing effective capacity
- Adding capacity
- Outsourcing work

The first two solutions based on reducing the variability give mixed results. Reducing the variability in workload on a day only affects the expected waiting time. For example, alving variance of workload on a day results in a reduction of 1.27 working days of waiting time, which is a 4.33% reduction of the total production lead time. Other variables like expected overtime days and overtime hours are not affected by this solution. Reducing the variability in employees present gives completely different results. When variance in employees on a day is reduced the expected waiting time barely changes, however there is an improvement in amount of expected overtime days and overtime hours needed.

The last three solutions based on reducing utilization levels give similar results, but differ in effectiveness. Increasing the effective capacity means improving the efficiency of work to get more done in less time. An increase of 5% in effective capacity is assumed to be possible. This leads to a reduction of 2.90 working days expected waited, a 9.90% reduction of the total production lead time. Adding capacity in the form of an extra employee has a massive impact on the production process. Doing this ensures a utilization below 85% that QRM advises. We find that adding one flexible employee that can work for 70% of the time in welding and 30% in assembly gives the lowest combined expected waiting time. Waiting time decreases by 4.43 working days, which is a reduction of 15.1% of the total production lead time and expected overtime days and overtime hours improve drastically. The final solution that we test is the effect of outsourcing work. Outsourcing 10% of welding work and 5% of assembly work is advised when choosing this solution. This leads to a reduction of 4.23 days in waiting time, a 14.4% decrease of the total production lead time. Expected overtime days and overtime hours decrease significantly as well. The last two solutions should not be combined. Both of these last two solutions are ranked as number one for being the best solutions based on feasibility, impact and cost.

The solutions are ranked with a weighted decision matrix. The solutions 'adding capacity' and 'outsourcing work' ranked first. It is not recommended to combine these two solutions. For the other solutions, the impact is not that significant or future research is needed before it can be implemented.

The biggest challenge of implementing one of the two best solutions is to get management on board. This solutions are based on QRM theory where utilization is advised to not be higher than 85%. This is much different to traditional ways of working. According to QRM it is worth it, since waiting times become less, the production environment becomes less uncontrolled and there is more time to work on improving.

7.2 Discussion

In Chapter 1, we state that the total waiting time between production phases needed to be reduced by 8.36 working days. After doing the current situation analysis in Chapter 2, the total waiting time between production phases on module level was 8.31 working days on average. This means that it was literally impossible to reach the target of 8.36 working days of waiting time reduced or 28.5% reduction of production lead time. In reality however, the waiting time between phases is assumed to be higher. This discrepancy can be explained by the fact that data is tracked on module-level and not on part-level. Due to the fact that data is tracked on module level, the model and the timeline (Figure 7.1) result in different values for waiting time at the welding department. It is also uncertain whether the action problem of not having 90% on-time delivery performance is fixed when one of the two best solutions is implemented. This is hard to determine, since this is not really tracked by Senro.

In this research, a Monte Carlo simulation model was made with which the current performance of the two departments discussed in this research can be calculated. With this model, Senro can run custom scenario's to see what the impact would be on the welding and assembly department. With this model, also some solutions to reduce waiting time were tested. The best solutions can reduce the expected waiting time by 4.43 days and 4.23 days respectively and also massively improve the overtime days and hours needed, however comes with quite some costs as a new employee needs to be hired or work needs to be outsourced.

Two of the five proposed solution approaches require future research before they can be implemented. The model shows the expected result of reducing variance in employees or increasing effective capacity, though this research does not provide the steps needed to reach that result.

This thesis can be used by Senro to get more insights into waiting times in their production process, as well as to gain general knowledge about what causes are of waiting time and what possible ways are to reduce them. Furthermore, the model made can be used to run potential scenario's to see how the welding and assembly department behave to changes to the given parameters.

7.3 Recommendations

Based on the research done and insights gotten during the making of the research, several recommendations can be made to the company:

- It is recommended to choose one of the following two solutions if Senro wishes to reduce waiting time and is convinced that lower utilization helps their production process:
    - Add flexible capacity where the extra person works for 70 percent of the time in the welding department and 30 percent in the assembly department.
    - Outsource 10% more work of the welding department and 5% work of the assembly department to external parties.
- It is recommended to divide the workload on a day more evenly. Currently the workload on a day is fluctuating quite a bit (see Figure 5.2). This means some periods have extreme peaks in workload, which asks a lot of the employees. Reducing the variance in workload on a day also reduces the average expected waiting time.
- The Monte Carlo simulation can be used to evaluate the performance of the welding and assembly department.
- In order to get a more accurate insight into the performance of the production process, it is recommended to track data on part-level rather than on module-level. Currently possibilities of ERP-systems are looked at, meaning that Senro is already working on this recommendation. The result is that future research will be more effective and efficient.

- The final recommendation to Senro is to start tracking data on the on-time delivery performance (better). On-time delivery performance is the action problem that this research tried to solve, however it is very hard to determine the current performance on on-time delivery performance and how much lead time reduction is needed to get this KPI to the 90% that Senro desires.

7.4 Contribution

In this section the theoretical and practical contributions of this thesis are discussed.

Theoretical contribution

In this research a literature review is performed on the QRM theory and reducing waiting times in an engineer-to-order production environment. This research does not contribute with new theories, however is more of a confirmation that the existing theories are correct and can be applied to a real problem.

Practical contribution

The first practical contribution of this research is the recommendations given in Section 7. Furthermore, this research gives insights into the waiting times that occur at Senro. With the Monte Carlo simulation model experiments are done that give a good insight on what happens with the performance of the welding and assembly departments with certain interventions. This can be valuable information to Senro.

7.5 Future research

Apart from the conclusion and recommendations described above, there are still some topics that could be interesting to do further research on:

- Increasing effective capacity is a good way to reduce waiting time due to the reduction of utilization levels. In this research, it is not explained how this can be achieved specifically at Senro. Future research on how to increase the effective capacity in the different production phases will be useful in decreasing the expected waiting time.
- This research focused on the welding and assembly department, it is recommended to also look at the laser cutting and bending phase and especially what happens before and after them.
- Quick-Response manufacturing is a companywide theory, so not only focused on the production process. An order is usually at the office for even longer, so it is recommended to research the impact of trying to reduce lead times at the office. The impact this might have on the total lead time of a module is can be bigger than by just looking at the production process.
- In this research we found out that reducing variability in present employees has no significant impact on waiting time, however it does result in a decrease in the amount of days where overtime is needed, as well as reducing the amount of extra hours needed per person when overtime occurs. That is why it is recommended to do future research on how to reduce the variance in employees present.

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Appendix A: Business process flow

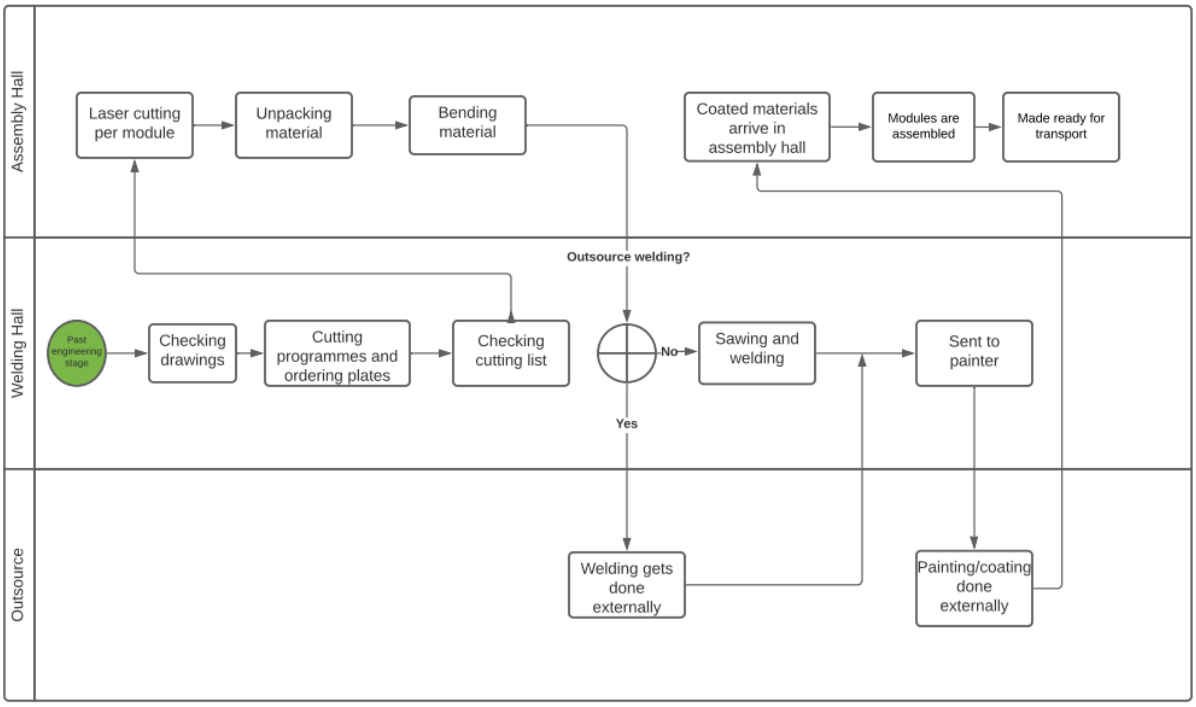

Figure A.1: Business process flow of production

Appendix B: Figures

AVG PROCESSING TIME PER MODULE (HOURS			
Phase	Big projects	All projects	Difference
laser_uren	7,96	4,06	3,90
kkw_uren	9,54	5,48	4,06
las_uren	53,05	38,95	14,10
cons_uren	4,50	8,83	-4,33
assem_uren	39,09	33,98	5,11

Figure B.1: Difference in processing hours big projects vs all projects

VC vs NC	TOTAL PC	TOTAL AC	Verschil (%)
Laser	2549,73	2447,41	-4,01%
Bending	3010,69	2741,75	-8,93%
Welding	15983,45	15792,75	-1,19%
Assembly	8505,73	11137,72	30,94%

Figure B.1: Difference between pre-calculation and after-calculation for working hours in production

Appendix C: Probability distributions

Appendix C.1 Distributions that fits input data

To determine the distributions of both of these data sets, some testing has to be done. All data sets given in section 4.3.1 are tested to identify the distribution that fits with these data. The significance level used is 5% (alpha is 5), meaning that there is a 5% margin for error. If the p-value is higher than 0.05, we can assume that the data set follows the distribution. If the data does not follow any distribution, we resort to making an empirical distribution. In this sub-section we first fully explain how the distribution is determined for one dataset. In Appendix C.2 all goodness of fit tests for the data sets are given, on which we can base the sort of distribution to use.

The data set that will be fully analyzed to fit a distribution is the total work on a day for welding. Minitab, which is a statistics software, is used to determine if the data set fits a certain probability distribution. An example of probability plots that can be made can be seen in Figure 4.5. If the blue data points are within the two outside red lines of the plots and the p-value is larger than 0.05, we can assume the data set follows that probability distribution. We can therefore conclude based on Figure 4.5 that the dataset does not follow any of the following distributions: normal, gamma, Weibull and lognormal

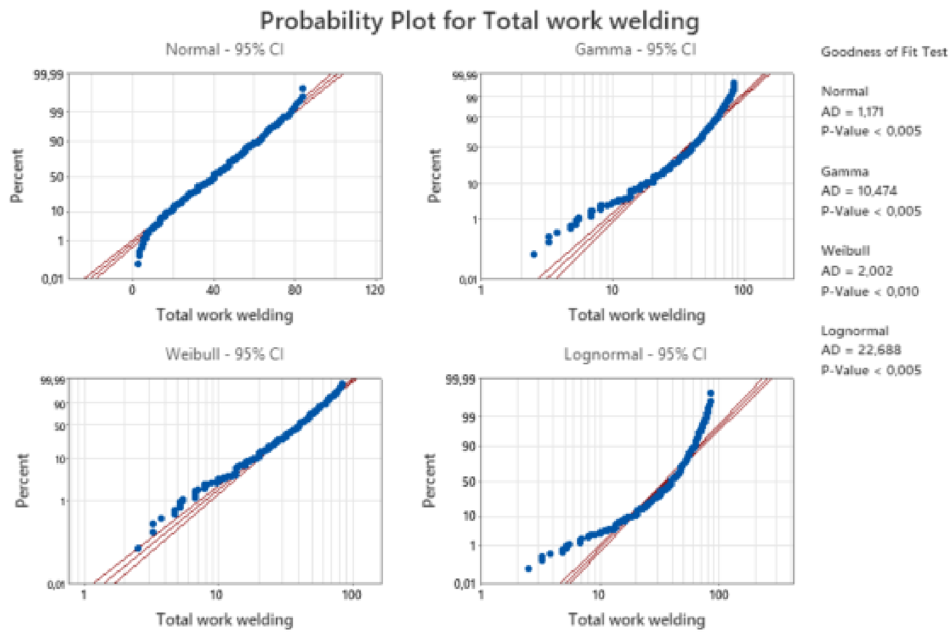

Figure C.1: Example of probability plots made for total work welding data set

With the help of Minitab, goodness of Fit Tests can be done on all probability distributions, giving the results as shown in Figure 4.6. As can be derived from the table, the data set does not fit any distribution. This is why we resort to using an empirical distribution for the total work done on a day at the welding department.

Appendix C.2 Goodness of Fit tests

Total work welding

Goodness of Fit Test

Distribution	AD	P	LRT P
Normal	1,171	<0,005	
Box-Cox Transformation	1,171	<0,005	
Lognormal	22,688	<0,005	
3-Parameter Lognormal	1,257	*	0,000
Exponential	147,121	<0,003	
2-Parameter Exponential	131,364	<0,010	0,000
Weibull	2,002	<0,010	
3-Parameter Weibull	0,961	0,009	0,003
Smallest Extreme Value	10,049	<0,010	
Largest Extreme Value	9,562	<0,010	
Gamma	10,474	<0,005	
3-Parameter Gamma	1,577	*	0,000
Logistic	2,392	<0,005	
Loglogistic	13,108	<0,005	
3-Parameter Loglogistic	2,425	*	0,000

Total work assembly

Goodness of Fit Test

Distribution	AD	P	LRT P
Normal	0,976	0,014	
Box-Cox Transformation	0,976	0,014	
Lognormal	10,803	<0,005	
3-Parameter Lognormal	0,172	*	0,000
Exponential	98,683	<0,003	
2-Parameter Exponential	97,085	<0,010	0,000
Weibull	0,839	0,031	
3-Parameter Weibull	0,921	0,012	0,023
Smallest Extreme Value	13,097	<0,010	
Largest Extreme Value	3,287	<0,010	
Gamma	3,274	<0,005	
3-Parameter Gamma	0,186	*	0,000
Logistic	0,765	0,026	
Loglogistic	3,132	<0,005	
3-Parameter Loglogistic	0,321	*	0,000

Hours worked PP welding per day

Goodness of Fit Test

Distribution	AD	P	LRT P
Normal	15,362	<0,005	
Box-Cox Transformation	15,066	<0,005	
Lognormal	18,081	<0,005	
3-Parameter Lognormal	15,057	*	0,000
Exponential	315,633	<0,003	
2-Parameter Exponential	260,401	<0,010	0,000
Weibull	25,304	<0,010	
3-Parameter Weibull	21,939	<0,005	0,000
Smallest Extreme Value	40,940	<0,010	
Largest Extreme Value	35,110	<0,010	
Gamma	15,754	<0,005	
3-Parameter Gamma	14,797	*	0,000
Logistic	10,393	<0,005	
Loglogistic	9,681	<0,005	
3-Parameter Loglogistic	9,800	*	0,000

Hours worked PP assembly per day

Goodness of Fit Test

Distribution	AD	P	LRT P
Normal	5,480	<0,005	
Box-Cox Transformation	5,480	<0,005	
Lognormal	20,606	<0,005	
3-Parameter Lognormal	5,468	*	0,000
Exponential	185,855	<0,003	
2-Parameter Exponential	180,614	<0,010	0,000
Weibull	10,151	<0,010	
3-Parameter Weibull	10,455	<0,005	0,155
Smallest Extreme Value	19,408	<0,010	
Largest Extreme Value	33,728	<0,010	
Gamma	12,308	<0,005	
3-Parameter Gamma	6,341	*	0,000
Logistic	1,281	<0,005	
Loglogistic	3,494	<0,005	
3-Parameter Loglogistic	1,288	*	0,000

Processing times of module welding

Goodness of Fit Test

Distribution	AD	P
Normal	111,854	<0,005
3-Parameter Lognormal	6,826	*
2-Parameter Exponential	48,662	<0,010
3-Parameter Weibull	3,165	<0,005
Smallest Extreme Value	206,589	<0,010
Largest Extreme Value	48,676	<0,010
3-Parameter Gamma	6,619	*
Logistic	61,603	<0,005
3-Parameter Loglogistic	7,861	*

Processing times of module assembly

Goodness of Fit Test

Distribution	AD	P
Normal	58,014	<0,005
3-Parameter Lognormal	3,522	*
2-Parameter Exponential	19,503	<0,010
3-Parameter Weibull	1,911	<0,005
Smallest Extreme Value	115,331	<0,010
Largest Extreme Value	24,629	<0,010
3-Parameter Gamma	3,620	*
Logistic	32,174	<0,005
3-Parameter Loglogistic	4,138	*

Appendix D: Monte Carlo simulation model

Appendix D.1 Generating input data for model

In this section it is explained how the data used as input for the model is generated. We explain how data is generated for one input variable. The input variable that is used for this explanation is hour worked per person on a day for welding. In Figure 4.7 it can be seen that a random number is generated, which is done for each individual variable, and also the hours worked per person on that particular day in the simulation: 10,75 hours.

Hours worked PP	
Welding	
0,976188414	10,75

Figure D.1: Model input for hours worked per person at the welding department

The 10,75 hours are gotten from the empirical distribution that was made for the input variable as can be seen in Figure 4.8. An example of what this table tells you is that around 25% of the time when a day is generated, the hours worked per person is 8 hours. This is the by far the most frequent hours worked per person on a day, which is very logical since a normal working day lasts 8 hours.

Hours pp welding	
0	4
0,010319917	4,25
0,012383901	4,5
0,013415893	4,75
0,015479876	5
0,025799794	5,25
0,034055728	5,5
0,04747162	5,75
0,057791538	6
0,076367389	6,25
0,101135191	6,5
0,116615067	6,75
0,216718266	7
0,286893705	7,25
0,353973168	7,5
0,422084623	7,75
0,49122807	8
0,758513932	8,25
0,787409701	8,5
0,801857585	8,75
0,825593395	9
0,857585139	9,25
0,878224974	9,5
0,901960784	9,75
0,919504644	10
0,943240454	10,25
0,95252838	10,5
0,970072239	10,75
0,979360165	11
0,991744066	11,25
0,996904025	11,5
0,997936017	11,75
0,997936017	12
0,998968008	12,25
0,998968008	12,5
0,998968008	12,75
0,998968008	13
1	

Figure D.2: Empirical distribution for hours worked per person welding

Input for total work on a day and processing times of modules are generated in a similar way. With these input variables the model can generate one day as shown in Figure 4.9. This is done 100.000 times and with all these days averages and likelihoods of certain outcomes can be seen. The same thing is done for the assembly department. A histogram is a good graph to visualize the distribution of different outcomes. The final results are shown in the model home screen, which is explained in the next section.

Total work welding	Hours worked PP welding	Processing times welding	Employees present welding	Utilization welding	Overtime hours welding
47,5	8	7,5	6	0,99	0

Figure D.3: One day in the simulation of welding department

The final part of generating the output for the Monte Carlo simulation that needs to be highlighted is about the experiments that can be done with the model. In the model there are some experiments the user can do. The user can run the simulation model with different scenario's. The changes the user can do is workload on a day, employees present on a day and variability levels for both the welding and the assembly department. The user input gets filled in at the place shown in Figure 4.10. In Figure 4.10 at the top you can see the current situation, below a random custom scenario. The way this changes the model is for example that when workload is upped by 8%, the total work on a day gets multiplied by 1.08 compared to the current situation.

Current scenario parameters	Extra employees	Workload change (%)	Variability change (%)	Moduletime change (%)
Welding	0	1	1	1
Assembly	0	1	1	1

Custom scenario parameters	Extra employees	Workload change (%)	Variability change (%)	Moduletime change (%)
Welding	1	1,08	0,98	0,99
Assembly	0	1,06	1,03	1,02

Figure D.4: Difference in parameters current situation vs custom

Appendix D.2 Model interventions

Table: Effects on output when only changing workload

Workload increase	Welding	Assembly
5% increase		
Total work	45,19	39,30
Employees	5,74	5,53
Utilization	0,95	0,89
Expected waiting time (days)	8,36	5,06
Overtime days (%)	57,05	24,89
Overtime hours	4,38	2,82
10% increase		
Total work	47,39	41,28
Employees	5,73	5,53
Utilization	0,96	0,92
Expected waiting time (days)	11,98	6,93
Overtime days (%)	64,50	35,13
Overtime hours	5,89	3,65
15% increase		
Total work	49,58	43,11
Employees	5,73	5,53
Utilization	0,97	0,94
Expected waiting time (days)	17,79	9,87
Overtime days (%)	74,96	51,89
Overtime hours	7,10	4,07
20% increase		
Total work	51,73	44,95
Employees	5,74	5,51
Utilization	0,98	0,96
Expected waiting time (days)	25,68	13,84
Overtime days (%)	87,28	65,84

Overtime hours	8,18	5,02

Table: Effect of adding or removing capacity in terms of employees

Employees increase/decrease	Welding	Assembly
-1 Employee		
Total work	43,05	37,46
Employees	4,74	4,52
Utilization	0,98	0,96
Expected waiting time (days)	20,16	16,52
Overtime days (%)	82,53	69,21
Overtime hours	8,09	5,43
+1 Employee		
Total work	43,07	37,41
Employees	6,73	6,53
Utilization	0,80	0,71
Expected waiting time (days)	1,90	1,29
Overtime days (%)	6,83	1,23
Overtime hours	3,40	2,61
+2 Employees		
Total work	43,08	37,44
Employees	7,74	7,54
Utilization	0,69	0,61
Expected waiting time (days)	1,07	0,70
Overtime days (%)	0,55	0,04
Overtime hours	2,43	1,54

Table: Effect of variability on the expected waiting time

Variability -/+	**Welding**	**Assembly**
-5% Variability		
Expected waiting time (days)	5,54	3,43
-10% Variability		
Expected waiting time (days)	5,52	3,14
+5% Variability		
Expected waiting time (days)	6,04	3,93
+10% Variability		
Expected waiting time (days)	6,22	4,24

Table: Effect of processing time per module on waiting time

Processing time per module -/+	**Welding**	**Assembly**
-5% Processing time		
Expected waiting time (days)	5,46	3,50
-10% Processing time		
Expected waiting time (days)	5,24	3,27
+5% Processing time		
Expected waiting time (days)	6,00	3,80

+10% Processing time		
Expected waiting time (days)	6,30	4,06

Appendix E: Manual of MC model

In this part of the appendix, a short manual of the Monte Carlo simulation model is given.

Monte Carlo Homescreen

The homescreen is the sheet on which the excel file opens. In the homescreen three different actions can be taken:

- *Run current situation:* A simulation is done based on the historical data from which output variables are gotten that represent the current situation
- *Run custom scenario:* A custom scenario can be made. You can fill in numbers to change the situation for eight different parameters. For each parameter you get a pop-up message as shown in Figure E.1. Make sure to fill in the numbers as explained in the message.

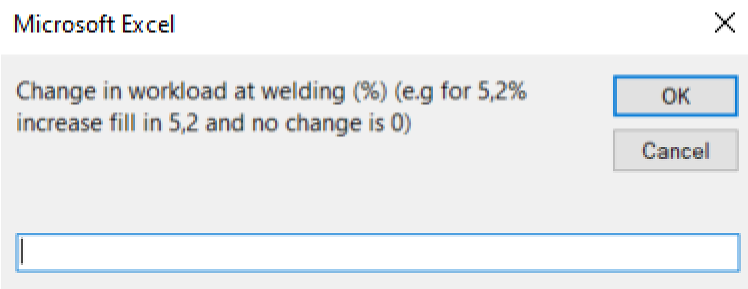

Figure E.1: Pop-up screen for changing parameter

- *Clear tables:* Pressing this button clears the tables on the homescreen. This also happens when the other buttons are pressed

What the homescreen looks like can be seen in Figure E.2.

Welding department	Average	Stdev
Total work (hours)	38,78	12,60
Employees	5,75	1,94
Utilization	0,85	0,09
Expected waiting time (days)	2,57	
Expected overtime days (%)	9,02	
Expected overtime hours	0,41	0,25

Assembly department	Average	Stdev
Total work (hours)	33,68	12,79
Employees	5,53	2,15
Utilization	0,76	0,08
Expected waiting time (days)	1,90	
Expected overtime days (%)	0,00	
Expected overtime hours	#DIV/0!	#DIV/0!

Adjusted parameters	Welding	Assembly
Workload (%)	-10	-10
Employees change	0	0
Variability (%)	0	0
Processing time (module) (%)	0	0

Figure E.2: Monte Carlo homescreen

The second sheet in the MC model is the 'Histograms output' sheet. From this sheet the distribution of the output variables can be seen. From these histograms some valuable information can be gotten. From the histogram the probability of the output variable being in a certain bracket can be derived. Total run length is 50000, so when the frequency of a certain bracket is for example 5500, you can derive that this relates to 11% probability.

Appendix E.3: Histogram sheet